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*Review*

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# Advancing Functionalized Track-Etched Membranes: Composite and Hybrid Materials through the JINR–South Africa Partnership

Track-etched polymer membranes (TeMs) are precision porous materials widely applied in water purification, sensing, and catalysis. However, their practical use is limited by hydrophobicity, fouling, and lack of functional activity. The purpose of this review is to synthesize the outcomes of the long-standing collaboration between South African institutions and the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna, Russia (FLNR, JINR), highlighting their contribution to overcoming these challenges. The objective is to present a focused survey of advances in TeMs functionalization, contextualized within global progress, and to assess their implications for applied membrane science. The methodology involved a structured literature survey (2007–2025) across Scopus, Web of Science, and Google Scholar, combined with critical evaluation of collaborative outputs. Emphasis was placed on peer-reviewed studies of metal sputtering, chemical grafting, and electrospun nanofiber composites. Results indicate that these approaches improve TeMs performance by enhancing hydrophilicity, mechanical stability, and catalytic or sensing functionality. Case studies include Ti/$TiO_2$ coatings for self-cleaning membranes, silver/gold nanoparticle-modified TeMs for surface-enhanced Raman spectroscopy, and nanofiber/TeMs hybrids for pollutant adsorption. In conclusion, the JINR — South Africa partnership demonstrates how targeted international collaboration can deliver impactful technologies. Future research should prioritize stimuli-responsive "smart" membranes, MOF-integrated hybrids, and roll-to-roll scale-up for industrial deployment.

*Keywords:* Track-etched membranes, Composite membranes, Hybrid materials, functionalisation, sputtering, electrospinning, nanoparticle integration, water purification, biosensing, JINR–South Africa collaboration

*Contents*

Dr. **Arnoux Rossouw** is a seasoned engineer and materials scientist, currently serving as Senior Scientific Researcher and Head of the National Group of the Republic of South Africa at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research (JINR) in Dubna, Russia. He holds a PhD in Electrical Engineering, an MSc in Electronic Engineering, and a BEng in Mechatronics, all from Stellenbosch University.

With over a decade of expertise, Dr Rossouw specializes in advanced materials and surface science, particularly physical vapor deposition, thin-film engineering, and magnetron sputtering—applications integral to track-etched membranes in water treatment, energy, and biomedical technologies. He leads strategic R&D projects, oversees JINR–South Africa collaborations, supervises MSc and PhD students, and drives grant acquisition.

Dr Rossouw has authored 20 publications, which have garnered 254 citations and over 1,600 reads on ResearchGate, reflecting his active academic engagement. His research includes the development of electrospun PVDF-functionalized PET track-etched membranes for desalination, nanofiber adsorbents for metal recovery from spent lithium-ion batteries, and composite membranes fabricated via roll-to-roll $Ti/TiO_2$ magnetron sputtering.

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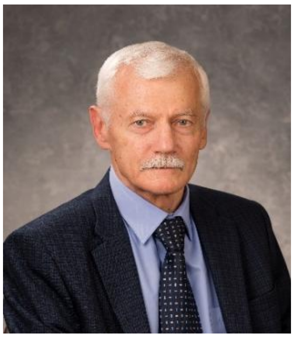
His research spans membrane and colloidal chemistry, nanomaterials, hydrogen technologies, and biomedical applications, with more than 80 Scopus-indexed publications (h-index 20) and over 140 total publications. Dr Nechaev's achievements have been recognized through awards such as the Gold Medal of the Russian Federation Exhibition of Achievements (2002) and the Bronze Award of the Russian National Foundation for Research in Nuclear Applied Physics (2003).



**Pavel Yurievich Apel** was graduated from the Leningrad Technological Institute in 1976. He has been pursuing his scientific career at the Flerov Laboratory of Nuclear Reactions in Dubna (Russia) where his activity is concerned with effects of accelerated heavy ions on polymers. At present he is the Head of Center of Applied Physics. In parallel, he was a Professor at the Dubna State University, where he gave lectures in 2008–2020. He published over 200 papers in peer-reviewed journals, some of which are recognized as significant contributions to the field, and co-authored 4 monographs. He was awarded the USSR Council of Minister's prize in 1989 and the Russian Federation Government prize in 2008 for the achievements in the field of science and technology. The main focus of his work is fabrication of micro- and nanostructures using the ion-track technique, including track-etched membranes and their application in academia and industry.

## *1 Introduction*

Membranes created by ion track etching are distinguished by uniformly sized, engineered nanopores formed via energetic heavy particle irradiation and chemical etching [1]. Polyethylene terephthalate (PET) is commonly used due to its mechanical and chemical stability, yielding TeMs with precisely controlled pore diameters, densities, and geometries [2, 3]. These unique structural features give TeMs advantages over conventional membranes — notably, well-defined pore architecture and narrow pore size distribution — enabling predictable transport and filtration properties [4]. TeMs have found diverse applications, from biomedical uses (virus filtration, plasmapheresis) to environmental monitoring and ultra-fine filtration. In particular, they are employed for high-purity filtration of air and liquids (including drinking water purification), as templates for nanomaterial synthesis, and as model membranes for fundamental studies [5].

While pristine track-etched membranes (TeMs) have exceptional precision and well-defined pore structures, their surface properties do not meet requirements of many applications, which leads, for instance, to susceptibility to fouling by organic compounds during filtration [6, 7]. Recognizing these inherent limitations, researchers have actively pursued strategies to enhance membrane functionality and broaden their practical applications [5, 8]. Over the past decade, significant progress has been made by introducing functional surface modifications and developing composite fabrication techniques. By incorporating functional materials such as metal thin films, nanoparticles (NPs), and polymer nanofibers onto TeMs, membranes have gained valuable new attributes, including improved hydrophilicity, catalytic capabilities, selective permeability, and responsive behaviours. These enhanced membranes, known as composite track-etched membranes (CTeMs), represent an exciting and rapidly growing category of high-performance materials. CTeMs effectively combine the precise pore control of traditional TeMs with innovative surface chemistries and functionalities, enabling broader and more impactful real-world applications.

This review focuses on advances in functionalized TeMs achieved through the JINR–South Africa partnership, alongside relevant external developments, from 2007 onward. South African scientists have collaborated with FLNR (JINR) to access heavy ion irradiation facilities and expertise in track-etch technology. Through this partnership, a series of studies has produced composite and hybrid membranes tailored for water purification, catalysis, and sensing applications. We first outline the SA–FLNR collaborative framework and major co-authored works. We then discuss key advances in TeMs modification techniques (metal sputter-coating, chemical functionalization, nanofiber layering, etc.) and the resulting membrane performance improvements [3]. Next, we highlight how these functional membranes have been applied in areas such as water treatment (pollutant degradation, fouling mitigation), and chemical sensing (e.g. detecting trace contaminants). Finally, we identify gaps in the current reference set — for instance, applications like oil–water separation or emerging fabrication methods like stimuli-responsive grafting — and recommend recent high-quality references to bridge these gaps.

By drawing together results from both the SA–FLNR collaboration and complementary international studies, this article offers a clear overview of the state-of-the-art in functionalised track-etched membranes. It highlights how joint research has advanced the field, while also identifying promising directions for future development. The review focuses mainly on water purification and sensing applications, but also considers emerging opportunities in catalysis, environmental monitoring, and biomedical use. To achieve this, we combined a systematic review of published literature with an assessment of experimental approaches developed within the JINR–South Africa partnership [9–13]. This dual perspective — combining a structured literature survey with collaborative experimental insights — sets the stage for the Methodology section, where we outline the review process and inclusion criteria in detail.

## *2 Methodology*

This article combines a systematic review of published literature with an overview of experimental approaches developed through the JINR–South Africa partnership.

The relevance of developments in the field of composite and hybrid nanomaterials is driven by the growing demand for high-performance filtration, separation, and adsorption technologies. The research of the team of authors focuses on the creation of track membranes (TeMs) with new functional properties by modifying the hydrophilic–hydrophobic balance of the surface, imparting photocatalytic activity, and creating specific selectivity. These properties are in demand in applications such as water desalination, rare earth extraction, radioactive contaminant purification, and rapid virus detection. TeMs modified with nanomaterials open up perspectives for innovative solutions in membrane technologies and medicine.

Our primary research goal is to enhance the performance and versatility of TeMs. Magnetron sputtering and electrospinning techniques provide a targeted and precisely controlled modification of the TeMs surface. Their use opens the way to the creation of composite and hybrid membranes with tailored functionalities, including increased durability, selective adsorption, and resistance to fouling, making them promising candidates for water purification, biotechnology, and medicine. Figure 1 summarises the concept and approaches developed in the articles to create new functional TeMs.

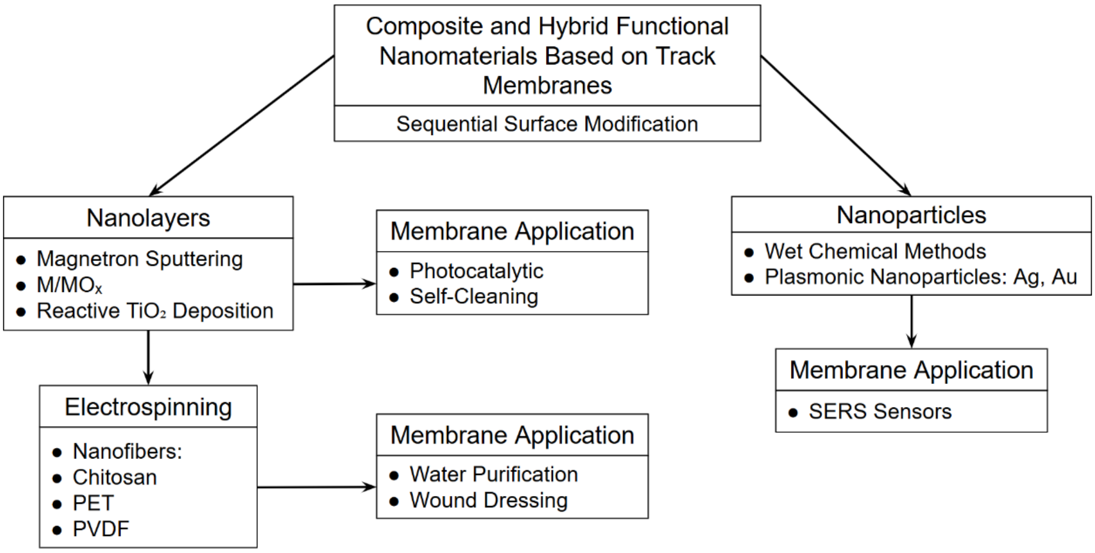



Figure 1. Conceptual schematic summarising functionalisation strategies for track-etched membranes (TeMs) — thin-film sputtering, chemical grafting/nanoparticle immobilisation, and nanofiber electrospinning — and their translation into key application domains

In addition to presenting the outcomes of our collaborative research, this paper follows the structure of a review article. Literature was systematically surveyed in Scopus, Web of Science, and Google Scholar using the keywords “track-etched membranes,” “functionalization,” “composite membranes,” “hybrid materials,” and “JINR South Africa collaboration.” Publications between 2007 and 2025 were prioritised to capture the full span of the partnership’s activities, with emphasis on peer-reviewed articles co-authored by South African and JINR researchers. To contextualise these works within global trends, additional high-quality international studies were included. Selection criteria excluded non-peer-reviewed reports, conference abstracts without full papers, and duplicated references. This methodological approach ensures that the review is both comprehensive and focused, while minimising redundancy and misaligned citations. Having established the review process, we next turn to the specific outputs of the JINR–South Africa partnership, beginning with an overview of its origins and representative collaborative works (Section 3).

## *3 South Africa — FLNR, JINR Collaboration Overview*

### *3.1 Origins and Framework*

Cooperation between South African research institutions and JINR’s FLNR began in the mid-2000s under bilateral agreements to build capacity in nuclear science and materials research. A notable milestone was the 5th South African–JINR Symposium in 2007, where prospects for using FLNR’s heavy ion accelerators for materials applications (including membrane fabrication) were discussed [14]. These discussions laid the groundwork for joint projects leveraging FLNR’s heavy-ion track technology and South Africa’s applied chemistry and nanotechnology expertise. In practice, FLNR’s cyclotrons in Dubna irradiate polymer films (often PET) to produce latent tracks, which are then chemically etched to form membranes with prescribed pore sizes and densities [2]. South African students and researchers have actively participated in this process, obtaining TeMs samples for further modification and testing in local laboratories. This section highlights representative publications co-authored by SA and FLNR researchers, underscoring the collaborative achievements.

*3.2 Metal Sputtering for Functional Coatings*

One major collaborative thrust has been the deposition of metal/metal oxide thin films onto TeMs to alter surface properties. Rossouw et al. demonstrated this approach by planar magnetron sputtering of titanium (Ti) and titanium dioxide ($TiO_2$) onto PET TeMs [14], see Figure 2.

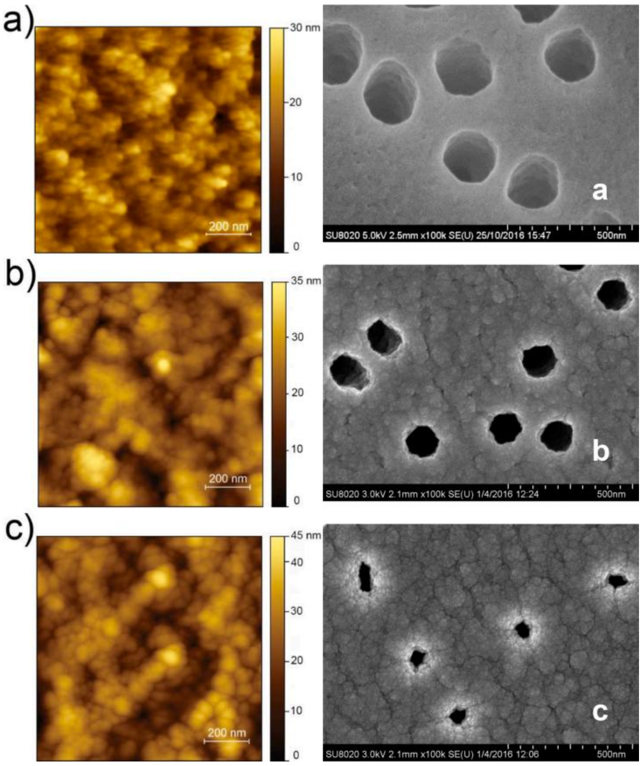



Figure 2. SEM and AFM images of PET track-etched membranes sputter-coated with titanium/titanium dioxide ($Ti/TiO_2$). Coated samples show uniform pore-wall coverage while preserving circular geometry, confirming functionalisation without pore blockage. (*a*) pristine TeMs, (*b*) Ti-coated TeMs, (*c*) $TiO_2$–Ti-coated TeMs. Reprinted from [15]. Copyright (2021) with permission from Elsevier

The $Ti/TiO_2$-coated membranes exhibited dramatically improved hydrophilicity — water contact angle dropped from ~72° (untreated PET) to ~43–45° after coating — and acquired photocatalytic activity under UV light [15]. These hydrophilic, self-cleaning surfaces mitigate organic fouling, a key issue in filtration [16, 17]. The study, published in 2021, was co-authored by researchers from JINR and South Africa (including Stellenbosch engineers and University of Western Cape chemists), reflecting a true partnership [15].

Notably, the TeMs themselves were produced at FLNR and then modified via sputtering to create hybrid membranes with a durable $TiO_2$ active layer. This work established that industrial sputtering is a viable method to functionalize porous polymer supports without occluding their pores [18], and it inspired follow-up efforts to scale up the coating process (see Future Directions).

*3.3 Electrospun Nanofiber–Track Membrane Composites*

The partnership has also explored integrating TeMs with nanofibrous layers to create hierarchical composites. Pereao et al. fabricated composite membranes by electrospinning chitosan/polyethylene oxide (CS/PEO) nanofibers directly onto a Ti-sputter-coated PET track-etched membrane [19, 20], see Figure 3.

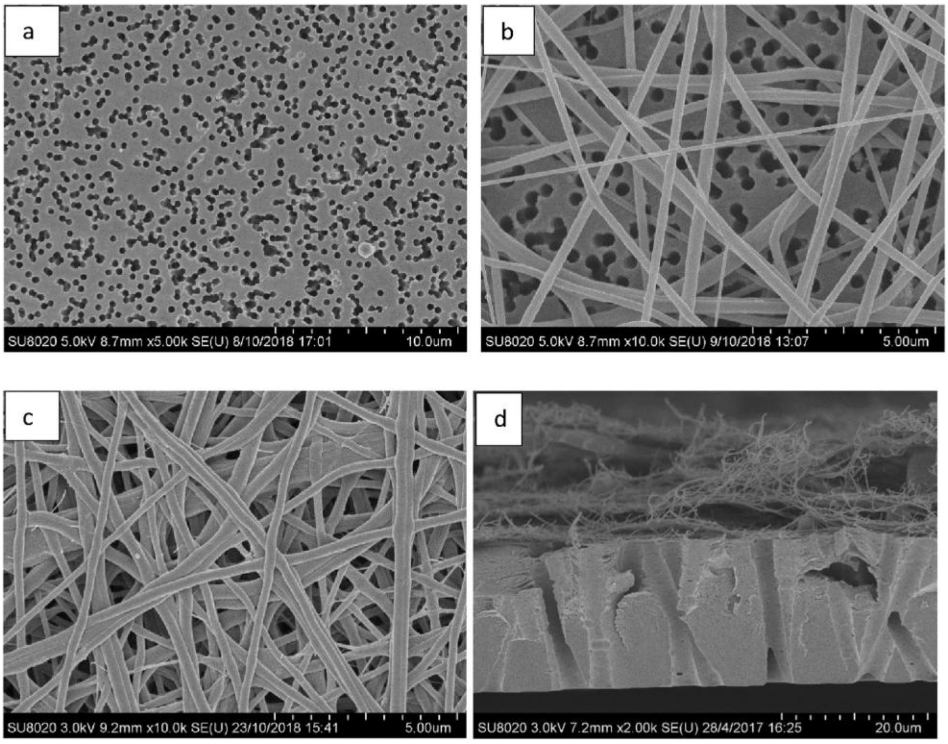



Figure 3. SEM micrographs of electrospun chitosan/polyethylene oxide (CS/PEO) nanofibers deposited on Ti-coated PET track-etched membranes. Cross-sectional images reveal hierarchical dual-scale porosity, with a nanofiber mat atop micron-scale track pores, enhancing adsorption, hydrophilicity, and mechanical stability. Reprinted from [19]. Copyright (2021) with permission from Elsevier

The Ti coating (deposited at FLNR) made the PET membrane electrically conductive and thus able to serve as the grounded collector for electrospinning. The resulting CS-nanofiber/Ti–PET composite exhibited a high surface area and new functionality: the chitosan nanofibers provide active adsorption sites and hydrophilicity, while the TeMs provide mechanical support and controlled microporosity. The authors demonstrated the composite's potential in water treatment, showing that it is stable in water (after crosslinking) and non-toxic to model aquatic organisms (Daphnia magna), indicating suitability for environmental use. They suggested such composites could be used as affinity membranes for capturing toxic heavy metals or organic pollutants from water [21]. This study [19] again involved JINR scientists (who provided irradiated PET films and technical expertise) and South African researchers who performed the electrospinning and application testing. It underscores a key collaborative achievement: combining two advanced fabrication techniques — ion track etching and electrospinning — to engineer a multifunctional membrane. Building on this, a 2025 follow-up by Bode-Aluko et al. extended the concept to nano-micro composite membranes by depositing different polymer nanofibers (polyamide-6 and polyacrylonitrile) onto track-etched PET. That study, supported by South Africa's DST and including an FLNR co-author (Nechaev), demonstrated effective removal of a model dye (Rhodamine 6G) in continuous filtration mode using the electrospun/track-etched membrane, outperforming standalone nanofiber or track-etched filters in dye rejection [21–23].

Taken together, these three approaches — thin-film sputtering, chemical grafting with nanoparticles, and nanofiber electrospinning — represent the main collaborative strategies of the SA–FLNR partnership. Each introduces distinct functionalities to track-etched membranes, ranging from improved hydrophilicity and photocatalysis to catalytic sensing and enhanced adsorption. This provides a cohesive framework for understanding the contribution of the partnership before situating it within the global context of membrane functionalization in Section 4.

In summary, the SA–FLNR partnership has yielded multiple novel composite membranes: metal-coated TeMs for anti-fouling and photocatalysis [15, 18], ligand-functionalized TeMs for nanoparticle-based sensing [24], and nanofiber-coated TeMs for enhanced adsorption and filtration performance [19]. Each of these projects combined JINR's track-etch materials with South Africa's applied research strengths, resulting in co-authored publications in international journals. The next sections delve deeper into the technological advances and applications demonstrated in these works.

### *4 Advances in Track-Etched Membrane Functionalization*

To fully unlock TeMs' potential, researchers have developed various post-etch modification techniques. Here we detail the main approaches — physical deposition, chemical functionalization, and composite fabrication — highlighting how they improve membrane performance. Collaborative SA–FLNR studies serve as prime examples of each approach, and we compare them with external progress in the field.

#### *4.1 Metal/Metal Oxide Thin-Film Coatings*

Depositing a thin inorganic film onto a polymer membrane can dramatically alter its surface characteristics without changing pore geometry too much. The Rossouw et al. study showed that a ~50–100 nm Ti/$TiO_2$ sputtered layer endows PET TeMs with hydrophilicity and photocatalytic ability [15, 25]. Before coating, PET is hydrophobic (contact angle ~72°) and prone to organic fouling; after coating with $TiO_2$, the membrane surface became hydrophilic (contact angle ~45°) and could leverage $TiO_2$'s well-known ability to generate reactive oxygen species under UV [15]. This means organic foulants can be more easily washed off or even degraded (self-cleaning membrane). The pores remained mostly open and circular post-sputtering [14, 26], indicating that planar magnetron sputtering — even in a roll-to-roll industrial setup — can uniformly coat the membrane without clogging (a crucial feasibility point). These advances illustrate that thin-film coatings (Ti, Cu, etc.) can introduce multiple functionalities — anti-fouling, photocatalysis, adsorption — to TeMs in a single modification step.

#### *4.2 Chemical Grafting and In-Pore Deposition*

An alternative to physical coating is to chemically attach new functionalities, either by forming chemical bonds on the pore walls or by template depositing materials inside pores. The SA–FLNR example of DETA grafting followed by silver electroless deposition fits here: first, surface amine groups were grafted via aminolysis of PET (introducing $–NH_2$ sites), then $Ag^+$ ions were bound and reduced to form Ag nanoparticles on the membrane [24], see Figure 4. This two-step wet-chemical process preserved the pore structure while adding a robust functional layer (in this case, enabling SERS and antimicrobial potential). These approaches highlight the tunability of track-etched pores: by either covalently attaching functional molecules or growing nanostructures within the channels, one can create membranes that not only filter by size, but also carry out chemical transformations (catalysis) or selectively bind contaminants (adsorption).

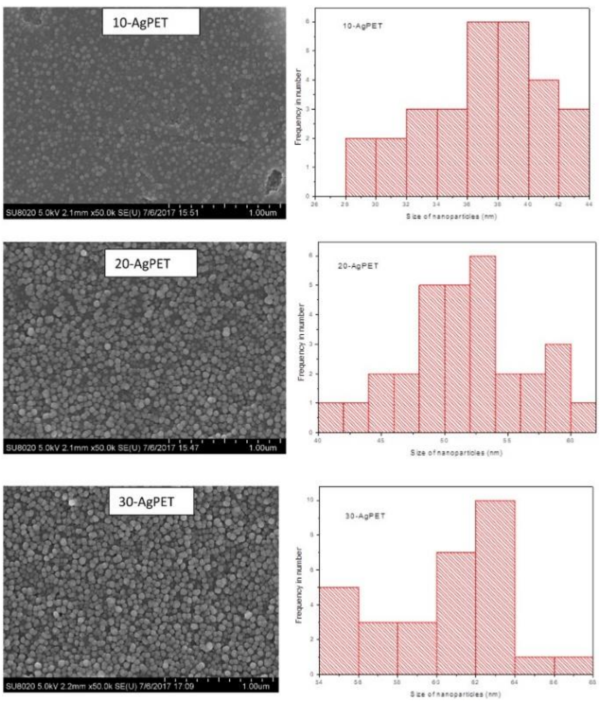



Figure 4. SEM images of silver-coated PET membranes prepared at 90 °C with 2 mL of 1 % trisodium citrate for immobilisation times of 10 min (10-AgPET), 20 min (20-AgPET), and 30 min (30-AgPET). Corresponding histograms show size distributions of silver nanoparticles for each sample, confirming growth in particle size with increased immobilisation time. Reprinted from [24]. Copyright (2021) with permission from Springer Nature

*4.3 Polymer Nanofiber Layering (Hybrid Membranes)*

By combining TeMs with electrospun nanofibers, researchers can create multilayer or hierarchical membranes that synergistically exploit the features of each component. The collaborative works by Pereao and Bode-Aluko are instructive — they directly electrospun nanofibers onto track-etched supports [19, 21]. The electrospun layer (whether chitosan-based or synthetic polymer) adds a mesoporous, high-surface-area network atop the TeM's well-defined through-pores. This dual-scale porosity (nano-fiber interstices and micropores in TeMs) can enhance filtration: the nanofiber mat can capture fine particulates or adsorb dissolved pollutants, while the underlying TeMs provide mechanical strength and a guarantee of maximum pore size (preventing any large breakthrough particles). Indeed, Bode-Aluko et al. found that a PA6-nanofiber/PET-TeMs composite achieved higher dye removal efficiency in continuous flow than an electrospun nanofiber filter alone, owing to the composite's improved permeability and support of the nanofiber layer. Another benefit is versatility — different functional nanofibers can be chosen (chitosan for metal ion binding, PAN for solvent resistance, etc.) to tailor the membrane to target contaminants. Elsewhere, researchers have developed analogous hybrids, for example coating TeMs with a chitosan hydrogel to make a reactive adsorbent membrane [20]. The concept of composite membranes extends to inorganic hybrids too: one can deposit materials like graphene oxide or metal–organic frameworks (MOFs) onto TeMs to impart new functions (e.g., adsorptive or catalytic sites) [27]. In all cases, the track-etched membrane acts as a precision scaffold that can be "decorated" with a secondary phase, yielding a membrane with enhanced functionality while maintaining predictable flow paths, see Figure 5.

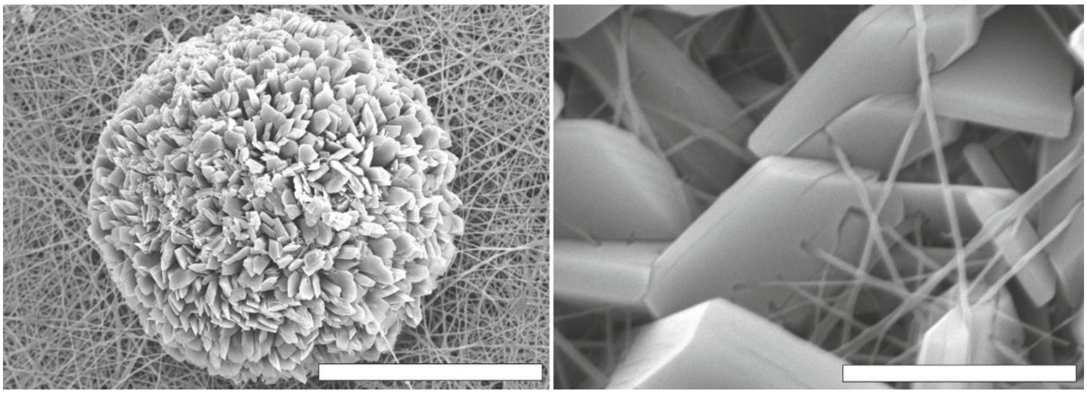


Figure 5. Surface micrographs of a TeMs + Chitosan + Ni-MOF sample at various magnifications; synthesis time: 24 h. Reprinted from [27]. Copyright (2024) with permission from Pleiades Publishing, Ltd.

Across these methods, a unifying theme is that functionalization does not sacrifice the unique order of track-etched pores. The JINR–SA studies carefully verified pore integrity via SEM/AFM and flow measurements after modifications [15, 18]. This is crucial: unlike many random-pore membranes, TeMs start with a well-characterized structure, and effective modifications must retain that structure (or modify it in a controlled way). The advancements above demonstrate that with the right techniques — whether physical vapor deposition, chemical grafting, or layer-by-layer assembly — one can introduce active functionality while preserving the engineered pore network of TeMs.

In summary, Section 4 illustrates that functionalization transforms TeMs from passive size-exclusion membranes into active, multifunctional materials. The SA–FLNR case studies stand as early demonstrations of this concept, while international work has expanded the field toward stimuli-responsive, MOF-integrated, and multi-scale hybrid membranes. This contextualisation strengthens the review by showing how local achievements connect with global research trajectories.

*5 Composite and Hybrid Membranes*

Functionalized track-etched membranes are often described as composite or hybrid membranes, reflecting their multi-material makeup. In this section, we examine the properties these composites exhibit and how they translate into performance improvements. We draw examples from both the JINR–South Africa papers and external literature to illustrate key points.

*5.1 Improved Hydrophilicity and Fouling Resistance*

Many polymer membranes (PET, polycarbonate, etc.) are hydrophobic, causing hydrophobic organic foulants to adsorb during filtration. Coating the TeMs with a more hydrophilic layer (whether inorganic or polymer) can mitigate this. Rossouw et al. reported that $TiO_2$-coated track membranes had significantly lower water contact angles and thus were less prone to fouling by organic matter [15]. Similarly, grafting hydrophilic polymers (like polyacrylic acid or polyvinylpyrrolidone) onto pore walls has been shown to create a hydration layer that resists protein or oil adsorption. In composite membranes from the collaboration, the inclusion of hydrophilic chitosan nanofibers rendered the surface much more wettable than bare PET [19, 20]. A practical outcome is extended membrane lifespan and flux: for instance, a $TiO_2$–Ti coated PET TeMs exhibited self-cleaning under UV irradiation — organic foulants were photocatalytically broken down, restoring water flux. This attribute is highly valuable in water purification systems where fouling is a primary cause of performance decline.

*5.2 Catalytic and Reactive Functions*

Composites that incorporate catalytic nanomaterials enable the membrane to actively degrade pollutants. The silver-loaded TeMs (both in the SA–FLNR SERS study and the external photocatalysis study) exemplify this. Ndilowe et al. mainly leveraged Ag for sensing, but silver is also known for antimicrobial and catalytic properties; a silver-coated membrane can inactivate bacteria and even catalyze reactions like dye reduction. In the work by Mashentseva et al., Cu/CuO loaded membranes could catalytically hydrogenate nitroaromatic pollutants (using $NaBH_4$ as a reducing agent) as water passed through, effectively functioning as a reactor in addition to a filter [28]. The same membrane could adsorb arsenic ions, as CuO is a known arsenic sorbent — this dual functionality (adsorption + catalysis) is a clear advantage of hybridization. Another example is $TiO_2$ coatings: beyond fouling control, $TiO_2$ under UV can oxidize organic pollutants in situ (e.g. breaking down trace pharmaceuticals during filtration) [15]. Thus, functionalized TeMs can be designed as active membranes that not only sieve out contaminants by size, but chemically neutralize or transform them. This expands the role of membranes in water treatment from passive barriers to reactive interfaces.

*5.3 Enhanced Selectivity and Sensitivity*

By incorporating recognition elements, TeMs can achieve selectivity for certain molecules or improved sensitivity in detection. The uniform pores of a TeMs are ideal templates for creating sensing channels; for instance, coating conical track-etched nanopores with responsive polymer brushes yields a sensor that modulates ionic current in response to specific chemical stimuli (pH, metal ions, etc.) [20]. In the SA–FLNR references, the SERS membrane is a great illustration: the membrane acts as a sample pre-concentrator (trapping analyte molecules on its surface) and as a SERS-active sensor, allowing trace detection of acetaminophen [24]. The limit of detection achieved (sub ppm) is competitive with lab instrument methods, yet the approach is field-deployable by simply dipping the membrane in water and then performing Raman analysis. This shows how hybrid membranes can serve as self-contained sensor substrates. External studies have pursued biosensing: for example, Torati et al. fabricated an electrochemical sensor for DNA by depositing gold nanowire arrays in track-etched pores and functionalizing them with DNA probes [29]. The resulting device could selectively detect Mycobacterium tuberculosis DNA sequences at low concentrations — something a plain polymer membrane could never do. These cases underscore that by grafting biomolecules or nano-sensors inside the well-defined pores, one can transform a TeMs into a highly sensitive and selective detection platform. The collaboration hasn't yet reported biosensing, but it has laid groundwork with the SERS chemical sensor and could extend to biosensors in future (indeed, the partnership's membrane was poised to detect other drugs and hormones in water [30]].

*5.4 Mechanical Stability and Throughput*

One often overlooked benefit of forming composites with TeMs is mechanical reinforcement and higher throughput. Electrospun nanofiber mats alone can be too fragile to use as standalone filters, especially at small fiber diameters. By spinning them onto a sturdy track-etched film (23 µm PET in Pereao's case [19, 20]), the resulting laminate can withstand handling and pressurized flow. The TeM's regular pore structure can also reduce flow resistance compared to a thick nanofiber mat, giving a more predictable permeance. Bode-Aluko's 2025 results indicated that the PA6/PAN nanofiber coated TeMs maintained good permeability while achieving high dye removal, benefiting from the hierarchical porosity (nano and micro) [21]. In another external study, track-etched membranes were used as a support for a thin selective layer in a composite nanofiltration membrane, significantly increasing water flux due to the low tortuosity of straight-through pores [31]. This concept is now being applied to develop thin-film nanocomposite (TFN) membranes where TeMs serve as support for ultra-thin selective coatings, marrying high flux of track pores with selectivity of the coating.

Taken together, these results demonstrate that composite and hybrid TeMs consistently outperform their single-component counterparts, whether by improving fouling resistance, catalytic activity, or mechanical durability. Importantly, they validate the principle that TeMs function not only as precision porous films, but also as scaffolds that can be adapted for diverse purposes by integrating nanomaterials and polymers. This forms a conceptual bridge between the materials-oriented innovations in Section 4 and their deployment in real-world scenarios, discussed in Section 6.

Collectively, these examples illustrate how composite/hybrid TeMs embody the adage "the whole is greater than the sum of its parts". By carefully combining materials, one designs membranes that are multifunctional — they can filter, catalyze, sense, and self-clean in one system.

## *6 Applications in Water Purification and Sensing*

The ultimate test of these advanced membranes is in real-world applications. Two areas of particular interest — and relevance to both South Africa and JINR's mission — are water purification (including treatment of wastewater or drinking water) and chemical sensing for environmental monitoring. The collaborative works have direct implications for these fields, as do several external studies we consider for context.

### *6.1 Water Purification Applications*

Access to clean water is a critical issue, and membranes play a central role in filtration-based water treatment (microfiltration, ultrafiltration, etc.). Track-etched membranes, with pore sizes typically in the micro- to sub-micron range (0.1–1 μm in many studies [15, 19]), are generally suited to microfiltration tasks like removing bacteria, protozoa, and particulate contaminants. However, by functionalizing TeMs, we can extend their utility to removing dissolved pollutants and even killing microbes, moving into realms usually served by adsorption media or chemical disinfectants.

Several of the reviewed membranes address organic pollutant removal. For instance, the $TiO_2$-modified PET TeMs can photocatalytically degrade organic molecules that foul the membrane surface [15, 32]. While Rossouw et al. focused on self-cleaning rather than bulk pollutant removal, the same principle could be applied to break down contaminants in the feed water (e.g., pesticide residues) as it passes through a $TiO_2$-coated membrane under UV illumination. In a South African context, where rural water may contain organic pollutants and limited infrastructure exists for advanced oxidation, such a membrane could provide a passive means of continuous water detoxification using sunlight. Expanding on photocatalysis, the silver microtubule PET membranes demonstrated complete decomposition of methylene blue dye under visible light [33], indicating that functional TeMs can harness even solar visible spectrum for water remediation. Dyes such as methylene blue or rhodamine are models for textile wastewater pollutants; the composite membranes loaded with Ag or CuO not only filtered these dyes but actively degraded them [28], achieving higher removal efficiency than size-exclusion alone.

Another pollutant class is heavy metals. While a plain PET membrane would not remove metal ions (they pass through the pores), a functionalized one can. The chitosan nanofiber composite is a prime example: chitosan's amine and hydroxyl groups have strong affinity for metal cations (e.g. $Pb^{2+}$, $Cd^{2+}$, [34, 35]). A CS-coated TeMs can thus serve as a binding membrane to strip metals from water. Pereao et al. suggested their CS/PEO-Ti/PET membrane could target toxic metals [32, 36, 37], and indeed chitosan-based filters are known to chelate metals effectively. In external work, poly(acrylic acid)-grafted TeMs loaded with iron oxide NPs have been used to adsorb arsenic and chromium from wastewater, functioning as a hybrid ion-exchange membrane [38]. The Cu/CuO-TeMs by Mashentseva et al. similarly achieved As(III) removal to meet <0.05 mg/L levels, which is the WHO guideline for arsenic in drinking water [28]. These capabilities are especially relevant to regions facing heavy metal contamination (e.g., mining-impacted waters in Southern Africa). A track-etched membrane functionalized for metal uptake could be deployed as a point-of-use filter that not only sieves out sediment and microbes but also scavenges dissolved metals — a multifaceted approach to water purification. Moreover, the same principle of functionalizing nanofibers can be applied to selectively recover metals of value from mixed hydrometallurgical solutions [37, 39].

Antimicrobial activity is another key application. Waterborne pathogens are traditionally removed by microfiltration (for bacteria) and ultrafiltration (for viruses), which TeMs can handle due to precise pore control. Functionalisation, however, adds a kill mechanism. Silver-coated TeMs are intrinsically antimicrobial because $Ag^{+}$ ions and nanosilver disrupt microbial cell membranes. Thus, the AgNP-functionalised TeMs developed in the JINR–South Africa collaboration could serve dual purposes: SERS sensing (as shown) and disinfection. Embedding biocidal agents into track-etched filters is a viable strategy: water passing through is both physically filtered and exposed to antimicrobial surfaces [21, 22]. Some commercial TeMs (e.g., polycarbonate filters) are already used for microbial analysis, and coatings could convert them into active barriers that prevent downstream bacterial growth. While the reviewed works did not yet quantify pathogen kill, this represents a clear and practical extension — particularly relevant to South African water treatment challenges.

*6.2 Sensing Applications*

Environmental sensing, especially pollutant detection in water, is a crucial application of functionalised TeMs. The importance of developing effective methods for monitoring emerging contaminants in aquatic systems has been emphasised in several reports, including work commissioned by the Water Research Commission [30]. In this context, the JINR–South Africa collaboration provided a clear proof-of-concept with AgNP-coated membranes applied as Surface-Enhanced Raman Spectroscopy (SERS) substrates. In this demonstration, the system enabled detection of acetaminophen at concentrations as low as 0.15 mg/L, highlighting the potential of TeMs-based SERS platforms for trace pollutant monitoring [24]. Such devices integrate sampling and sensing in one step: analytes are concentrated during filtration and then identified using a portable Raman spectrometer, without complex sample preparation. This proof-of-concept illustrates how functionalised membranes could be developed into field-deployable kits for monitoring pharmaceuticals, pesticides, and other contaminants in water.

Beyond SERS, track-etched membranes can be incorporated into electrochemical sensors. For example, a conductive track-etched membrane (such as one sputter-coated with a thin metal film) can act as a working electrode with a well-defined porous structure. Researchers have used gold-coated TeMs to detect heavy metal ions via anodic stripping voltammetry, with the pores facilitating rapid diffusion of ions to the electrode surface. Another avenue is biosensing: functionalizing pores with aptamers or enzymes that produce a readable signal when a target analyte is present. A notable case, as referenced earlier, is the DNA-functionalized Silver or Au nanotube arrays for detecting specific DNA sequences (like pathogens) [24, 29, 40]. The uniform pore geometry of TeMs yields consistent sensor response across the membrane area, which is advantageous for reproducibility.

The South African context offers many relevant sensing targets: monitoring of emerging contaminants (pharmaceuticals, endocrine disruptors) in water bodies, detection of pathogens, and even security applications like detecting explosives or toxins. Functionalized TeMs can be tailored to these — for instance, a membrane with molecularly imprinted polymer within its pores could selectively bind a pesticide and include a reporter dye to signal its capture. The groundwork laid by the SERS membrane shows how to marry chemistry with the TeMs platform for sensing. Given that FLNR has expertise in radiation chemistry, one future collaboration could involve grafting radiolabelled or luminescent groups in pores to create scintillating membranes for radiation sensing or radiochemical detection.

These applications highlight the dual strengths of the JINR–South Africa work: addressing urgent South African water challenges while also contributing globally relevant sensing technologies. By linking membrane structure directly to pollutant removal or analyte detection, the partnership illustrates how collaborative science can translate fundamental modifications into practical outcomes. This prepares the ground for identifying gaps and outlining future research priorities in Section 7.

In summary, water purification and sensing are being redefined by these advanced membranes. Instead of using separate units for filtration, adsorption, and detection, multi-functional TeMs strive to do all simultaneously: filter out what you can, degrade or bind what you can't filter, and even indicate what contaminants were present. The JINR–South Africa partnership's prototypes — photocatalytic membranes, adsorptive nanofiber composites, and SERS membranes — embody this integration. In the next section, we discuss what gaps remain in the current repertoire of references and how further research (some already underway elsewhere) can fill those gaps, moving the technology closer to practical deployment.

## *7 Gaps and Future Directions*

While the collection of references reviewed demonstrates significant progress, there are notable gaps and emerging opportunities in functionalized TeMs that have not yet been fully covered by the SA–FLNR works. Identifying these gaps is important to chart future collaboration efforts and to position the research within global membrane science trends. Below, we outline key areas that warrant further exploration, along with suggested high-quality references that could guide these investigations:

*7.1 Stimuli-Responsive "Smart" Membranes*

None of the current SA–FLNR studies explicitly dealt with stimuli-responsive gating membranes. These are membranes that alter their permeability in response to environmental triggers (pH, temperature, light, etc.). Incorporating stimuli responsive polymer brushes or hydrogels into track-etched pores can create membranes that act as on-demand valves — for instance, open at high pH and closed at low pH, useful for controlled drug delivery or self-regulating filtration [11, 20]. Recent breakthroughs include optothermally responsive TeMs grafted with PNIPAM-metal nanocomposites that change flow in response to light, and block copolymer grafted TeMs that separate oil–water emulsions by switching hydrophilicity with pH [41, 42]. These "smart" membranes represent a cutting-edge direction that the collaboration could pursue. A 2023 study by Muslimova et al. reported a PET TeMs grafted via RAFT polymerization with a styrene/acrylic acid copolymer, achieving tunable wettability and successful oil-water separation [42]. Integrating similar stimuli-responsive layers in JINR-fabricated TeMs could lead to membranes that adapt to feed conditions (e.g., resisting fouling by switching to hydrophobic when oil is present, then to hydrophilic for cleaning).

*7.2 Broader Application Spectrum*

Beyond water pollutants and SERS sensing, track-etched membranes are also being explored for gas separation and biomedical applications. Gas separation is challenging due to the relatively large pore size of TeMs, but integrating ultra-thin selective coatings [43] could yield hybrid membranes suitable for vapor or gas filtration. In life sciences, TeMs are emerging as cell culture templates or scaffolds for tissue engineering, with their pores enabling nutrient flow and cell migration pathways [44]. They are also being investigated as artificial membranes for organ-on-chip devices [45].

Another gap relates to anti-biofouling and antimicrobial performance. While Section 6.2 highlighted the dual use of AgNP-coated membranes developed within the South Africa–FLNR partnership, future collaborative studies should directly test functionalised TeMs against bacteria and viruses under realistic conditions. Recent reports show, for instance, that copper nanoparticle-embedded polymer membranes achieve >99 % bacterial inactivation [46]. Incorporating such studies — alongside photocatalytic examples like visible-light active $TiO_2$ membranes inactivating *E. coli* [47] — would strengthen the case for JINR–South Africa membranes as comprehensive water treatment solutions.

*7.3 Advanced Composite Architectures*

To date, the composite membranes developed through the JINR–South Africa partnership predominantly integrate polymers, metals, and metal oxides. However, there remains an exciting gap in incorporating emerging nanomaterials, particularly two-dimensional (2D) materials (such as graphene and MXenes) and Metal–Organic Frameworks (MOFs) [48].

For instance, 2D nanosheets could be strategically coated onto TeMs to impart selective barrier properties for smaller contaminants or introduce conductive functionalities. MOFs, renowned for their porous crystalline structures, offer a promising avenue to add highly selective adsorption or catalytic sites to membranes. Recent research demonstrated functionalizing PET track-etched membranes with Ni-based MOFs using chitosan as a linker, significantly enhancing adsorption capacities for organic molecules [27]. Such hybrids, leveraging both macro-porosity of TeMs and nano-porosity of MOFs, represent an exciting advancement in multi-scale filtration technology. This type of integration is underrepresented in current collaboration literature, marking a logical next step for future collaborative studies.

*7.4 Scale-Up and Practical Deployment*

Beyond material composition innovations, scaling the fabrication of functionalized TeMs from laboratory to practical, real-world applications remains a critical challenge. The collaboration has begun addressing this with initiatives such as Rossouw's pioneering work on roll-to-roll sputtering methods, explicitly aimed at achieving continuous, industrial-scale production of functionalized membranes [18]. However, practical scale-up strategies and methods remain largely underrepresented in the current body of references.

Future studies should prioritize pilot-scale demonstrations, including the production and field-testing of larger-scale (e.g., square-meter) rolls of functionalized track membranes. Such membranes could be evaluated in realistic operational environments, such as integrated water treatment modules or in sensor cartridge configurations for environmental monitoring. A pivotal reference in this context is [18] study on the industrial-scale production and integration of track membranes into practical devices, providing valuable engineering insights and guidance on large-scale manufacturing and handling.

Furthermore, addressing economic and lifecycle considerations, such as coating durability, membrane regeneration strategies, and fouling resistance under realistic water conditions, is essential yet currently missing from the collaboration's literature. Incorporating perspectives from environmental engineering literature, such as studies on long-term ultrafiltration membrane fouling by Lee et al. from 2017, will be crucial for ensuring the next generation of functional TeMs are both effective and practically viable [49].

*7.5 Infrastructure Development*

Complementing material and process innovations, infrastructure enhancements are also central to advancing functionalized track-etched membrane research. In South Africa, iThemba LABS provides a unique national platform that supports both nuclear science and applied materials studies. Its cyclotron facilities, originally established for nuclear physics and medical isotope production, also offer ion-beam capabilities that can be adapted for track-etch membrane fabrication and modification. Beyond beamlines, iThemba LABS houses complementary facilities such as cleanrooms for sample preparation, thin-film deposition equipment, and advanced characterization instruments (SEM, RBS, PIXE), which are critical for developing and testing membrane materials.

Importantly, iThemba LABS is not only a research hub but also a training environment, where South African students and researchers gain hands-on experience with ion beam techniques and materials science applications. In this way, it complements JINR's infrastructure in Dubna, enabling a bilateral pathway where membranes can be fabricated, modified, and tested across both sites. Strengthening this integration provides opportunities to expand the collaborative outputs of JINR and South Africa, and lays the foundation for scaling laboratory innovations toward real-world applications.

*7.6 Outlook*

The gaps we have identified also point to exciting opportunities for future work. Track-etched membranes are moving toward becoming smarter, easier to produce on a larger scale, and increasingly tailored for specific applications. By introducing responsive grafting methods [50], exploring the potential of new nanomaterials [50], and focusing on practical scale-up [27], the JINR–South Africa partnership can continue to play a leading role in this field. If these directions are pursued, functionalized membranes could take on a much wider range of challenges — from simple, self-cleaning water filters to compact "lab-on-membrane" systems for environmental monitoring — helping to push membrane technology into its next stage of development.

In sum, Section 7 highlights both the unmet challenges and promising opportunities that remain for functionalized TeMs. By identifying where the SA–FLNR partnership can contribute — such as in smart membranes, MOF and 2D hybrids, and pilot-scale roll-to-roll fabrication — the discussion provides a forward-looking framework that connects naturally to the overall conclusions in Section 8.

## *8 Conclusions*

In conclusion, the JINR–South Africa partnership has become a notable contributor to membrane science, marrying fundamental research (ion track physics, surface chemistry) with pressing applied needs (clean water and environmental sensing). The composite and hybrid TeMs developed under this collaboration illustrate the power of international cooperation in addressing multidisciplinary challenges. By continuing to fill knowledge gaps — adopting intelligent polymer grafts, exploring new composites like MOF@TeMs, and focusing on pilot-scale production — the partnership is poised to drive further innovations in functional membranes. These advanced membranes have the potential not only to improve water quality and analytical detection in South Africa and the Eurasian region, but also to serve as globally relevant solutions in the quest for sustainable and smart water treatment technologies.

The joint efforts of JINR's FLNR and South African researchers over the past ~15 years have significantly advanced the field of functionalized track-etched membranes. By uniting the precision of ion-track nanotechnology with innovative chemistry and nanomaterials engineering, this partnership has produced composite membranes that transcend the traditional role of passive filtration. These works represent a cycle of interconnected studies in which diverse methods for fabricating nanostructured track membranes were tested under real conditions and their efficiency confirmed, with results published in highly cited Russian and international journals.

Key outcomes include:

– Hydrophilic, antifouling membranes via metal oxide coatings, which maintain high flux and self-cleaning properties, showing promise for more sustainable water filtration;

– Catalytically active membranes that degrade organic pollutants or adsorb heavy metals during filtration, achieved by embedding nanoparticles or catalytic coatings on TeMs — merging separation and reaction in one step;
– Sensing membranes, such as the silver-coated SERS platform, capable of capturing and detecting contaminants in situ, introducing a new paradigm of "analytical membranes";
– Hierarchical composite membranes combining nanofiber mats with track-etched films, which improve adsorption capacity and mechanical robustness by leveraging multi-scale porosity.

This review also related these achievements to global research trends, highlighting complementary studies (e.g., electroless deposition of metal microtubes, grafted responsive polymers) that broaden the implications of the collaborative works. While the references cover strong foundations in water-related applications and sensing, there is still scope to expand into smart membranes, advanced composite architectures (such as MOF@TeMs), and scaling techniques. Encouragingly, steps toward roll-to-roll modification already suggest translation to industry, while emerging studies on stimuli-responsive TeMs provide a blueprint for adaptive next-generation membranes.

In conclusion, the JINR–South Africa partnership has become a notable contributor to membrane science, marrying fundamental research with pressing applied needs in clean water and environmental sensing. By continuing to address these gaps and extending collaborative innovation, the partnership is well-positioned to drive future advances in functional membranes. These membranes have the potential not only to improve water quality and analytical detection in South Africa and the Eurasian region but also to contribute globally to sustainable and smart water treatment technologies.

Ultimately, the JINR–South Africa partnership serves as a model of how targeted international collaboration can transform niche nanomaterials research into technologies with broad societal relevance, bridging laboratory innovation with real-world impact.

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### *Conflicts of Interest*

The authors declare no conflict of interest.

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