

Investigations into New Micro- and Nano-Coating Strategies for Technological and Biomedical Applications

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Over time, micro- and nano-coatings have evolved from simple passive protective layers into complex, functional surface systems capable of dictating interactions at the material–environment interface [1–3]. Advancements in surface engineering, nanotechnology, and materials design have increased our ability to adjust coating composition, microstructure, and functionality, enabled by the continuous development of high-performance characterization and processing equipment. In this field, ongoing technological upgrades are essential for improving the precision, reproducibility, and accuracy of measurements at both the micro and nano scales [4–6]. In this context, coatings are no longer solely viewed as a response to degradation phenomena such as corrosion or wear, but rather as technologies that address critical challenges in environmental sustainability, energy security, and biomedical engineering.

This Special Issue, entitled “New Strategies and Recent Advances in Investigations of Micro- and Nano-Coatings for Technological and Biomedical Applications”, has attracted substantial attention from the scientific community by collating studies that reflect this multidisciplinary landscape; it has currently accumulated over 25,000 views and more than 50 citations. Rather than focusing on a single application, the collected works can be viewed through three interconnected pillars: environmental protection and sustainability, energy systems and advanced infrastructure, and medical and biomedical applications. Together, these contributions demonstrate how micro- and nano-coatings can function as strategic tools for sustainable development, enhancing safety, and improving quality of life.

The first pillar addresses the growing role of coatings in environmental remediation and sustainable preservation. Water and soil are being contaminated by toxic heavy metals, posing long-term risks to ecosystems and human health and representing a pressing environmental issue. In this context, coating-based materials derived from biodegradable and renewable resources offer a promising alternative to conventional remediation technologies [7,8].

In their study, Cai et al. report the development of biodegradable chitosan–gelatine–hydroxypropyl methylcellulose (CS–GEL–HPMC) composite membranes for the remediation of cadmium-contaminated water and soil. By systematically varying HPMC content, the authors demonstrated that membrane composition strongly influences structural stability, surface morphology, and adsorption, with the CS30–GEL30–HPMC40 formulation exhibiting the best performance. In aqueous systems, this optimized membrane reduced Cd²⁺ concentrations from 1 ppm to approximately 0.53 ppm within 60 min, corresponding to a removal efficiency of ~47%. When applied to contaminated soils, the membrane reduced pore-water Cd²⁺ concentrations from ~250 µg·L^{−1} to 15–20 µg·L^{−1} over a period of 42 days.



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Further optimization through the application of mineral additives identified cement as the most effective synergistic agent, reducing extractable Cd to below $60 \mu\text{g}\cdot\text{kg}^{-1}$ [9].

Environmental protection also extends to the conservation of metallic cultural heritage, where surface treatments must meet strict requirements related to reversibility, transparency, and low toxicity; traditional protective coatings often fail to satisfy these criteria [10].

In this regard, with the aim of protecting copper artifacts from corrosion, Ioan et al. developed hybrid nanocomposite coatings based on organo-modified silica matrices which incorporated ZnO nanoparticles and benzotriazole (BTA), functioning as eco-friendly alternatives to conventional acrylic lacquers. Using a sol–gel route with tetraethoxysilane (TEOS) and 3-glycidyloxypropyl trimethoxysilane (GPTMS) precursors, the authors obtained transparent, homogeneous coatings, provided that the ZnO nanoparticle content remained below 2 wt%. Colorimetric analysis revealed that silica-based coatings containing moderate ZnO concentrations produced total color differences (ΔE^*) of approximately 5.1–6.1, whereas higher ZnO loadings (3 wt%) led to pronounced visual alteration ($\Delta E^* > 10$). Electrochemical testing in 3.5 wt% NaCl solution demonstrated that silica coatings modified with ZnO and BTA achieved corrosion rates comparable to the reference material (Incralac) [11].

Together, these studies illustrate how micro- and nano-coatings can not only mitigate pollution but also contribute to the sustainable preservation of culturally significant materials.

The second pillar focuses on coating applications in energy systems and advanced infrastructure, where they are essential for ensuring safety and durability under extreme operating conditions. In the nuclear energy sector, zirconium-based alloys are widely used as fuel cladding materials due to their favourable neutronic and mechanical properties. However, their susceptibility to rapid oxidation under accident conditions has motivated extensive research into surface-engineered solutions [12].

Addressing the need to enhance the safety and durability of nuclear energy systems, Diniasi et al. investigated the performance of chromium coatings deposited through electron-beam physical vapor deposition on Zircaloy-4 (Zy-4) fuel cladding, focusing on their accident-tolerant behaviour under CANDU reactor primary circuit conditions. A $\sim 2 \mu\text{m}$ thick Cr layer was subjected to long-term autoclaving in lithiated water (pH 10.5) at 310°C and 10 MPa for up to 3024 h and subsequently evaluated. Microstructural characterization showed that the Cr coating remained adherent and continuous throughout exposure, while cross-sectional SEM confirmed that coating integrity was preserved and the oxide thickness increased without delamination. Electrochemical impedance spectroscopy demonstrated a substantial increase in coating resistance with autoclaving time, reaching values on the order of $10^{11} \Omega\cdot\text{cm}^2$ after 3024 h, consistent with improved barrier properties [13].

Advanced coatings are also critical for improving the mechanical and functional performance of structural materials used in demanding technological environments. Focusing on the role of surface topography, Omran et al. investigated the influence of substrate roughness on the properties of nanocrystalline diamond (NCD) films deposited on Ti-6Al-4V (TA6V) alloys. Using Raman spectroscopy, they confirmed a dominant diamond phase with sp^3 contents between 83% and 91%, while X-ray diffraction revealed well-defined diamond (111), (220), and (311) reflections. Surface profilometry and interferometric analyses showed that NCD deposition increased the roughness from approximately 50–90 nm for polished TA6V substrates to 110–150 nm after coating. Microhardness measurements revealed an increase in surface hardness, with values rising from ~ 320 HV for uncoated TA6V to ~ 340 HV for NCD-coated samples polished with the finest grit [14].

The third pillar is dedicated to medical and biomedical applications, in which micro- and nano-coatings are designed to actively interact with biological environments. Metallic biomaterials such as titanium alloys are widely used for orthopedic and dental implants.

However, their long-term performance is often limited by corrosion processes, ion release, and susceptibility to bacterial colonization. Beyond conventional alloys, the recent emergence of medium- and high-entropy alloys has opened new opportunities for advanced biomedical materials with superior mechanical strength and corrosion resistance [15,16].

Exploring multicomponent alloy coatings as a strategy to overcome the limitations of conventional titanium implants, Chen et al. investigated the mechanical performance, corrosion resistance, and elution behaviour of TiNbTa and TiNbTaZr thin films deposited on Ti-6Al-4V substrates via co-sputtering. By tailoring the elemental composition and valence electron concentrations (VECs) of 4.17 to 4.90, the authors demonstrated a clear structure–property relationship, with the films exhibiting either mixed HCP/BCC or single BCC phases depending on VEC values. Mechanical characterization revealed a significant enhancement in surface hardness, particularly for Ta-rich compositions, with values reaching 12.1 GPa for the Ti₈Nb₈Ta₇₉Zr₅ film compared to 4.9 GPa for bare Ti-6Al-4V, while Young's modulus varied between 108 and 226 GPa depending on the phase constitution. Electrochemical testing in a 3.5 wt.% NaCl solution showed markedly improved corrosion resistance for selected quaternary coatings, with polarization resistance values up to $2.9 \times 10^4 \text{ k}\Omega\cdot\text{cm}^2$, corresponding to an Rp ratio of 6.4 relative to the uncoated alloy. Long-term immersion (for a period of eight weeks) in Ringer's solution confirmed the formation of a dense, amorphous surface oxide layer (~10 nm thick), effectively inhibiting the elution of Al and V ions from the substrate, as evidenced by XPS depth profiling. These results identify Ti₃₃Nb₁₉Ta₂₁Zr₂₇, Ti₁₅Nb₆₈Ta₈Zr₉, and Ti₈Nb₈Ta₇₉Zr₅ coatings as particularly promising candidates that can be used to improve the corrosion resistance of titanium implants while enabling biocompatible surface modification [17].

In another contribution that bridges advanced alloy design with bioactive surface functionalization, Stoian et al. deposited complex chitosan–bioglass–ZnO composite coatings on a 73Ti–20Zr–5Ta–2Ag alloy using a doctor blade, aiming to enhance corrosion resistance and antibacterial performance for orthopedic applications. Morphological SEM and EDS analysis confirmed the formation of homogeneous polymeric films, with bioglass particles (≈ 500 – 2500 nm) and ZnO nanoparticles (≈ 200 – 300 nm) partially embedded within the chitosan matrix. This led to an increase in surface roughness from $0.6 \text{ }\mu\text{m}$ for chitosan-only coatings to $1.4 \text{ }\mu\text{m}$ for the composite system. Electrochemical testing in a 0.9 wt% NaCl solution demonstrated the composite coating's substantial improvement in corrosion protection, with the current density decreasing from $3.6 \times 10^{-7} \text{ A}\cdot\text{cm}^{-2}$ in the bare alloy to $3.4 \times 10^{-8} \text{ A}\cdot\text{cm}^{-2}$, and the polarization resistance increasing to $1.43 \times 10^7 \text{ }\Omega\cdot\text{cm}^2$. Importantly, antibacterial assays against *Staphylococcus aureus* and *Escherichia coli* revealed growth inhibition efficiencies of 83% and 75%, respectively, after 48 h of incubation. This study demonstrates how bioactive composite coatings can effectively complement multicomponent titanium alloys [18].

Controlled drug delivery is another important application of biomedical coatings. Rather than serving solely as protective layers, coatings can function as reservoirs for therapeutic agents, enabling localized and controlled drug release [19,20].

Addressing the challenges associated with biodegradable metallic implants, including infection control and corrosion, Voicu et al. deposited polylactic acid (PLA) coatings loaded with gentamicin sulphate (GS) on AZ31 magnesium alloy using two scalable techniques, dip coating and electrospinning, systematically comparing their structural, electrochemical, and antibacterial performance. As demonstrated by morphological analyses, the electrospun coatings consisted of randomly oriented PLA nanofibers with diameters of approximately 500 nm, whereas the dip-coated films formed continuous mesoporous layers with pore sizes around 1– $1.5 \text{ }\mu\text{m}$. Electrochemical testing in simulated body fluid (SBF, pH 7.4) demonstrated the improved corrosion stability of both coatings relative to bare AZ31.

Adhesion measurements further highlighted the superiority of the dip-coated films, which exhibited an adhesion strength of 4.99 MPa, compared to 1.66 MPa for nanofibrous coatings. Drug-loading studies indicated a higher gentamicin encapsulation efficiency for dip-coated PLA (73%) than for nanofibers (65%). Antibacterial assays against *Staphylococcus aureus* and *Escherichia coli* confirmed a strong synergistic effect between PLA and gentamicin, with inhibition indices reaching 69.8% for *S. aureus* and 55% for *E. coli* in the GS-loaded dip-coated samples [21]. These findings emphasize the importance of micro- and nano-structural control in the design of multifunctional biomedical coatings.

Zirconium-based systems are a particularly illustrative example of how advanced materials have evolved across disciplinary boundaries. Initially exploited for their low thermal neutron absorption cross-sections and excellent corrosion resistance in nuclear reactor environments [22], zirconium alloys and oxides have become increasingly relevant in biomedical and pharmaceutical applications due to their chemical stability, tuneable surface chemistry, and generally favourable biocompatibility [23].

In this context, Radu and Drăgănescu provide a comprehensive review of ZrO₂ nanostructures as platforms for drug loading and controlled release. They highlight how the morphology of nanostructures, encompassing nanoparticles, nanosheets, nanotubes, and nanoporous films, governs their loading efficiency and release kinetics. Different drug-loading strategies are examined, including physical adsorption, covalent bonding, electrostatic interactions, diffusion, degradation, and stimulus-responsive release mechanisms, and relates them to drug properties and environmental conditions. The review also explicitly addresses existing challenges such as burst release, long-term stability, concentration-dependent toxicity, and the lack of standardized synthesis routes and clinically relevant in vivo validation methods. By integrating examples from cancer therapy, antimicrobial treatments, bone regeneration, and dental applications, the authors position ZrO₂ nanostructures as versatile, functionally active surfaces which represent an intersection between materials science and biomedicine [24].

Taken together, the contributions presented in this Special Issue demonstrate that micro- and nano-coatings are central to the design of advanced material systems. Across the domains of environmental, energy, and biomedical applications, they enable surface interactions to be precisely controlled, directly influencing performance, safety, and sustainability. Although each application presents distinct challenges, common themes emerge, including interface engineering, multifunctionality, and long-term stability.

Future research efforts are expected to focus on multifunctional and responsive coatings, improving our understanding of their long-term behaviour under realistic service or physiological conditions, and the integration of sustainability considerations into coating design and processing [25–27]. By bringing together fundamental research and application-oriented studies, this Special Issue aims to stimulate interdisciplinary collaboration and contribute to the continued advancement of micro- and nano-coating technologies for next-generation technological and biomedical applications.

Conflicts of Interest: The authors declare no conflict of interest.

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