

Multifunctional Polymeric Coatings with Engineered Topographies for Clinical Environments: A Review of Antimicrobial Mechanisms and Tribological Surface Modification

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Abstract

Clinical steel work surfaces lack inherent antimicrobial properties and present low friction coefficients, creating traction deficiencies and sanitary vulnerabilities. This review synthesises recent advancements in multifunctional organic coatings engineered to replace pristine metallic substrates. We evaluate the chemical integration of quaternary ammonium compounds (QACs), metal-oxide resins, and structural MXene nanosheets within polymer matrices. Furthermore, we analyse how micro-textured topographies balance anti-biofluid accumulation with tactile mechanical traction. Finally, we outline structural strategies to optimize long-term mechanical, chemical, and thermal coating resilience.

Keywords

Functional Organic Coatings, Contact-Killing Polymers, Surface Topography, Quaternary Ammonium Silicones, Tribological Wear Resistance

1. Introduction

The purpose of this review is to evaluate alternative surface materials for application in veterinary practice examination rooms and pre-operative preparation tables. The overarching goal is to identify materials that mitigate animal stress, min-

imize handling injury risk, and enhance sanitation, ultimately creating a safer clinical environment. For decades, veterinary examination tables have been constructed of medical-grade stainless steel, a durable, cost-effective, and easily sanitized material. Austenitic 304 and 316 stainless steels have served as the industry standard due to their high corrosion resistance, ease of sterilisation, and structural longevity [1]. However, from an operational, mechanical, and biochemical standpoint, pristine stainless steel tables possess structural limitations that compromise both patient welfare and clinical efficiency [2].

The primary operational issue is that stainless steel exhibits an extremely low friction coefficient, prohibiting animals from gaining secure tactile traction. This smooth metallic surface is highly problematic under the specific intended use conditions of veterinary clinics, which cater to diverse animal species spanning a wide size range, from small companion animals (e.g., cats and exotic pets weighing under 5 kg) to large canine breeds exceeding 50 kg. During routine examinations, these surfaces face both dry and wet exposure conditions, including contact with biological fluids (urine, blood, saliva, and faeces), liquid antiseptics, and routine water-washdowns. Under these conditions, the lack of sufficient static and dynamic friction causes the animal's paws to slide during posture adjustments. When animals cannot gain tactile traction and balance, they experience heightened physiological anxiety and acute kinetic stress. This instability prompts frantic attempts to regain balance, making it more difficult and dangerous for veterinarians and veterinary technicians to manually restrain and examine the patient. Furthermore, induced anxiety can lead to defensive or aggressive animal behavior, posing physical threats to both handlers and the animals themselves. Designing clinical environments that provide reliable traction outcomes is essential to minimize the need for forceful physical restriction, thereby making clinical procedures safer and more efficient.

In addition to operational limitations, stainless steel is not inherently antimicrobial. Its cleanliness depends entirely on periodic, manual chemical disinfection by clinic personnel [2]. This reliance creates a significant hygiene gap, a window of vulnerability between consultations where pathogens can accumulate and cross-contaminate successive patients. To bridge this gap, modern macromolecular and materials engineering research has focused on designing functional surfaces and smart organic coatings within a multi-functional framework. A dedicated coating for veterinary applications requires long-lasting, non-leaching, broad-spectrum antibacterial activity, a controlled non-slip topography that avoids trapping biofluids, and dynamic moisture management to prevent liquid pooling. The macromolecular network must also feature exceptional mechanical, chemical, and thermal durability to withstand claws, dropped surgical instruments, and harsh disinfectants, while maintaining low raw-material and processing costs to remain economically viable for widespread deployment. This review synthesises recent material engineering developments to evaluate composite polymeric coatings as alternatives to bare stainless steel.

Review Methods

To ensure a rigorous synthesis of the literature, a systematic search strategy was executed across primary electronic databases, including PubMed, Scopus, Google Scholar, and Web of Science. The eligibility criteria restricted the scope to peer-reviewed research articles, review papers, and technical reports published between 2010 and 2025 focusing on contact-killing polymers, metal-containing resin composites, photocatalytic coatings, stimuli-responsive surfaces, and micro-textured topographies. Evidence was drawn from diverse fields, including human healthcare, food processing, marine anti-biofouling settings, and veterinary practice. To synthesize this cross-disciplinary data, evidence from human clinical trials was prioritized when assessing surface pathogen reduction dynamics. Materials performance data, including tribological properties and wear resistance under harsh environments, were extensively drawn from marine and food processing literature. However, findings from non-veterinary sectors were critically weighed and adjusted to account for the unique mechanical stresses (e.g., localized claw forces) and environmental conditions characteristic of veterinary examination rooms.

2. Antimicrobial Mechanisms in Polymer Matrices

In the design of antimicrobial organic surfaces, a fundamental division exists between strategies that employ a contact-killing mechanism to destroy pathogens and those that inhibit microbial adhesion to prevent biofilm development [3] [4]. Surfaces that exclusively prevent microbial adhesion do not actively kill pathogens. In high-traffic clinical areas such as pre-operative wards and examination rooms, anti-adhesive surfaces can allow viable pathogens to persist, increasing the risk of mechanical transmission via cross-contamination. Conversely, contact-killing approaches leave less room for microbial persistence by actively disrupting the pathogen upon contact [3]. By integrating active components directly into the material matrix, these surfaces can help bridge the hygiene gap caused by inconsistent manual sanitation, though they do not entirely eliminate the necessity of periodic physical cleaning. A combined approach leveraging both repellent and contact-killing properties has demonstrated robust performance, achieving up to 99.9% bacterial and 98% viral reductions in vitro using substrate-independent bi-functional spray coatings [5].

When evaluating these technologies, it is clinically vital to distinguish between distinct performance metrics: *antimicrobial surface activity* (the inherent capacity of a material to kill microbes in vitro), *reduced surface bioburden* (the measurable decrease in colony-forming units on real-world surfaces), *reduced cross-contamination* (the lowered rate of pathogen transfer between surfaces or vectors), and *reduced clinical infection risk* (the actual decrease in healthcare-associated infection rates among patients). These outcomes are frequently treated as interchangeable in early-stage literature, but they represent entirely separate clinical thresholds that depend heavily on environmental confounding variables.

Contact-killing polymeric surfaces employ polycationic networks, quaternary

ammonium coatings, antimicrobial peptides, immobilised enzymes, metal-oxide nanoparticles, and graphene to directly harm microbes [3]. Within this domain, mechano-bactericidal nanostructures, such as those utilizing cicada-wing biomimicry or graphene nanospikes, aim to destroy the microbial membrane physically without releasing chemical agents. Currently, these mechano-bactericidal surfaces are being adapted from biomedical implants to the food-processing industry to prevent biofilm formation and bacterial colonization [6]. The structural principles governing these surfaces are also utilized in marine engineering to minimize microbially influenced corrosion [4].

Alternative chemical release strategies have been explored across various industries. For instance, in indwelling biomedical models, portable and wearable nitric oxide-releasing polymer inserts have been developed to deter bacterial adhesion and biofilm formation by maintaining controlled, localized nitric oxide delivery for up to 24 hours [7]. While effective at reducing bacterial viability by over 90% in targeted catheter applications, such release mechanisms require defined donor replenishment and present safety controls that limit their suitability for permanent, large-scale tabletop coatings [6] [8]. Furthermore, the stability and structural lifecycle of such organic matrices are highly sensitive to dynamic humidity and moisture absorption, which govern water interactions within the bulk polymer network [9].

The integration of metallic elements into polymer matrices represents a distinct approach. Silver-impregnated foils applied to high-touch hospital surfaces have demonstrated success in controlled human healthcare studies, yielding a measurable log reduction in surface bioburden over a six-month period compared to non-antimicrobial controls [10] [11]. Similarly, copper-based surfaces have been evaluated clinically; a pragmatic hospital field study utilizing copper-oxide-infused resin surfaces on high-touch objects observed a reduction in pathogen recovery, though the overall quality of evidence was limited by environmental biases [12]. A broader review of copper surface interventions supported a possible benefit in reducing ambient surface bioburden within clinical environments [13]. Crucially, while these studies confirm reduced surface bioburden, direct correlation to a reduced clinical infection risk requires more extensive epidemiological validation. Furthermore, although metal nanoparticles show significant bactericidal potential via ion release, concerns persist regarding their long-term cytotoxicity and environmental accumulation upon degradation. Natural antimicrobial compounds, such as essential oils or plant-derived polyphenols, offer superior biocompatibility but suffer from high volatility, low long-term potency, and significant batch-to-batch variability, rendering them insufficient for rigorous clinical applications.

Photocatalytic and stimuli-responsive coatings represent the next tier of functional surface design. Photocatalytic coatings typically incorporate semiconductor nanoparticles like titanium dioxide. Under ultraviolet (UV) illumination, these semiconductors undergo excitation, generating highly reactive oxygen species (ROS), such as singlet oxygen, superoxide radical anions, and hydroxyl radicals, which in-

duce oxidative damage to microbial nucleic acids, lipids, and proteins [10]. However, the efficacy of photocatalytic coatings is highly variable and depends on light intensity, exposure time, and surface availability. The prerequisite for high-energy UV light introduces operational challenges, and while recent research explores visible-light activation, current configurations lack sufficient energy efficiency for rapid ambient sterilization. Stimuli-responsive coatings are engineered to alter their surface chemistry or release active agents in response to environmental triggers such as light, temperature, moisture, pH, or electrical signals. Mechanically responsive, self-shedding surfaces represent a unique subset of this category. For example, layer-by-layer self-assembled, nano-crumpled MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) coatings fabricated on flexible poly(dimethylsiloxane) (PDMS) substrates exploit sharp-edged nanostructures to kill microbes on contact, while utilizing on-demand physical deformation (stretching or flexing) to mechanically shed over 99% of adhered bacterial cells, effectively restoring surface cleanliness [11].

3. Tribological Surface Modifications and Design Hypotheses

Transitioning these material technologies to veterinary exam tables requires a comprehensive understanding of polymer tribology. Introducing micro-textured topographies to polymer matrices introduces critical design trade-offs between wet traction, cleanability, fluid retention, abrasion resistance, and chemical disinfectant exposure (see summary in Table 1).

Table 1. Tribological and functional trade-offs of polymeric surface micro-topographies in veterinary clinical environments.

Design attribute	High micro-texture (deep valleys/sharp peaks)	Low micro-texture (flat/polished surface)	Proposed shallow pebble texture
Wet traction	Excellent; provides high mechanical interlocking for animal paws.	Poor; hydrodynamic lubrication causes hydroplaning and slipping.	Moderate-to-high; provides sufficient static/dynamic friction.
Cleanability	Poor; biofluids and debris become trapped in deep recesses.	Excellent; easily wiped clean with standard mechanical pressure.	Good, smooth, rounded ridges permit efficient wiping.
Fluid retention	High; micro-capillary forces retain moisture and organic waste.	Very low; liquids pool macroscopically or drain freely.	Low; prevents fluid pooling without trapping micro-droplets.
Abrasion resistance	Vulnerable; high aspect-ratio peaks face severe mechanical shear from claws.	High; uniform stress distribution minimizes localized wear.	High; low-profile, rounded features distribute abrasive loads.
Disinfectant exposure	High vulnerability; chemical residues accumulate in valleys, accelerating degradation.	Low vulnerability; chemical solutions are easily wiped away completely.	Moderate-low; minimal residue retention prevents accelerated polymer aging.

A deeply textured polymer maximizes paw traction under wet conditions but creates high fluid retention and compromises cleanability, as biological debris and harsh disinfectants accumulate within the valleys, accelerating chemical degradation. Conversely, a completely smooth surface optimizes cleanability and abrasion resistance but fails to provide the necessary traction when exposed to fluids, reintroducing the slipping hazards of stainless steel.

To balance these competing requirements, a shallow pebble texture is proposed. This topography utilizes low-profile, rounded nodules that project sufficiently above the fluid boundary layer to provide adequate tactile grip for animal paws under wet and dry conditions. Concurrently, the valleys remain shallow and smooth, minimizing capillary fluid retention and allowing standard veterinary disinfectants and organic wastes to be easily removed by routine mechanical wiping. The rounded geometry also mitigates localized stress concentration, enhancing the coating's resistance to abrasion from animal claws.

To implement this tribological design alongside advanced biochemistry, we propose a novel design hypothesis for empirical validation: an integrated, multi-tiered surface architecture consisting of a rigid, copper-oxide-infused composite resin tabletop base supplemented by a removable, micro-textured elastomeric antimicrobial mat. In this hypothetical framework, the base tabletop provides a baseline contact-killing effect to reduce surface bioburden across the bulk material, ensuring that the antimicrobial activity is not confined to a fragile surface film prone to scratching. The optional elastomeric mat, engineered from a flexible silicone or polyurethane matrix, can incorporate contact-killing agents, such as tethered quaternary ammonium compounds or nano-crumpled MXene matrices, to afford enhanced compliance, physical comfort, and specialized pathogen defense.

Crucially, the simultaneous incorporation of QACs and MXene nanosheets within the *same* material layer remains unexamined in contemporary literature, and their chemical compatibility within a single unified matrix has not been established. Consequently, this multi-tiered architecture is presented strictly as a design hypothesis requiring extensive compatibility testing, wear characterization, and *in situ* microbiological validation before clinical deployment can be recommended.

4. Discussion

Developing an optimal replacement for stainless steel veterinary tables requires balancing mechanical practicality with antimicrobial performance. While photoactive and stimuli-responsive coatings show promise *in vitro*, their operational limitations render them less practical for ambient veterinary environments. Photocatalytic TiO₂ coatings require continuous, unobstructed light exposure to sustain antimicrobial surface activity. In clinical practice, the surface directly beneath an animal patient is obstructed by fur, paws, and organic matter, creating immediate sanitation gaps where light cannot penetrate. Furthermore, retrofitting examination rooms with specialized UV lighting arrays introduces economic and

safety burdens. Similarly, stimuli-responsive release mechanisms triggered by moisture or pH fluctuations are poorly suited for permanent table surfaces. Animal skin secretions, sebum, and variable hair coats can interfere with polymer response triggers, and erratic chemical release dynamics conflict with the strict patient safety controls required in veterinary facilities.

Consequently, passive contact-killing architectures offer a more reliable framework. Copper-oxide composite resins stand out as the most clinically grounded option for the primary tabletop substrate, given their documented capacity to reduce ambient surface bioburden without requiring external light or electrical stimuli [12] [13]. To complement this baseline table structure, the proposed design hypothesis introduces a flexible, removable polymer mat. By utilizing a stretchable elastomeric substrate like PDMS, the system can leverage the mechano-bactericidal properties of self-shedding nanostructures, such as the nano-crumpled MXene multilayers described by Asadi Tokmedash *et al.* [11]. Under this configuration, the sharp-edged peaks of the crumpled MXene sheets exert localized mechanical stress on adhering bacterial membranes, while the inherent flexibility of the mat allows for intentional physical deformation to shed dead microbial biomass [11]. This self-shedding behavior addresses a primary limitation of static contact-killing polymers, which often suffer from surface blinding as dead microbial debris accumulates and masks the active chemical sites.

5. Conclusion

A completely optimized material system capable of eliminating the veterinary sanitation gap and surface traction deficiencies remains an active area of research. Based on current materials engineering data, the most promising strategy involves a transition from bare stainless steel to a passive, multi-tiered material system. This approach is best framed as a design hypothesis combining a rigid, copper-oxide-infused bulk resin tabletop with a shallow pebble texture to balance wet traction, cleanability, and long-term wear resistance. This primary surface can be supplemented with a removable, flexible elastomeric mat incorporating advanced contact-killing networks or self-shedding, nano-crumpled MXene topographies to facilitate biomass removal through mechanical deformation. Future empirical research must focus on validating the wear resilience of these micro-textured polymers against repetitive claw abrasion and determining whether measured reductions in surface bioburden translate directly into a verifiable reduction in cross-contamination and clinical patient infection risk.

Author Contribution

T. Kovács and O. Betts contributed equally to the literature compilation, screening, tribological analysis, and manuscript drafting.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this pa-

per.

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