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REVIEW

Multilevel antimicrobial polymers (MAP-1): Advanced coating strategies for pathogen control

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ABSTRACT

Multilevel Antimicrobial Polymer (MAP-1) coatings represent a transformative advancement in surface disinfection technologies, offering long-term and broad-spectrum protection against a variety of pathogens, including bacteria, viruses, and fungi. Designed for compatibility with diverse surfaces such as metal, plastic, glass, and textiles, MAP-1 exhibits strong adhesion, low cytotoxicity, and resistance to environmental degradation. This review explores the chemical composition, application methods, and real-world utility of MAP-1 in settings ranging from healthcare and public transport to schools and textiles. Antimicrobial efficacy studies and international validation protocols such as ISO 22196 are critically discussed. The article further contrasts MAP-1 with conventional coatings like silver- and copper-based systems, highlighting its cost-effectiveness and reduced environmental footprint. Despite its advantages, scalability and regulatory challenges persist. Future perspectives include the integration of smart functionalities and AI-guided material optimization. MAP-1 holds significant promise in addressing current gaps in infection control, especially in high-touch environments, offering a sustainable approach to mitigating surface-borne disease transmission.

KEYWORDS

MAP-1 coating; Antimicrobial polymer; Surface coating technology; Pathogen-resistant

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Introduction

The global outbreak of infectious diseases, notably the COVID-19 pandemic, has underscored the critical importance of effective surface disinfection strategies. While conventional cleaning methods and disinfectants offer short-term microbial control, they often fail to provide sustained protection and require frequent reapplication. This has driven the demand for innovative antimicrobial surface coatings that deliver continuous, long-lasting, and broad-spectrum pathogen resistance. In this context, Multilevel Antimicrobial Polymers (MAP-1). Schematic illustration of MAP-1 showing multilevel defense mechanisms: polymer matrix, antimicrobial moieties, and surface interaction layers (Figure 1) have emerged as a promising solution [1].

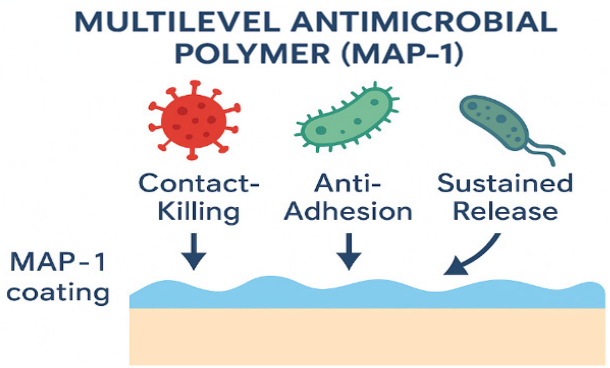

Figure 1. Multilevel antimicrobial action of MAP-1.
(**Source**. Gao et al., ACS Applied Materials & Interfaces, 2020)

Developed by the Hong Kong University of Science and Technology (HKUST), MAP-1 is a versatile antimicrobial coating designed to deactivate a wide spectrum of microorganisms, including viruses, bacteria, and fungi. What makes MAP-1 particularly noteworthy is its multilevel antimicrobial action, which combines contact-killing, anti-adhesion, and controlled-release mechanisms to offer both immediate and prolonged microbial suppression. This multifunctional performance is achieved through the integration of polymeric matrices embedded with quaternary ammonium compounds and other biocidal agents, forming a thin, flexible, and invisible film on various surfaces [2].

MAP-1 has been applied in high-risk public areas such as hospitals, schools, transportation systems, and elevators, where microbial contamination poses a persistent threat. Unlike traditional antimicrobial coatings that may lose effectiveness due to wear, surface erosion, or microbial resistance, MAP-1 exhibits excellent mechanical durability, biocompatibility, and surface adherence, ensuring efficacy for up to 90 days after a single application [3].

In addition to its physical robustness, MAP-1 is designed to be environmentally friendly and safe for human contact, a critical factor for applications on high-touch surfaces such as textiles, plastic, glass, and metal. It does not leach harmful chemicals into the environment and is considered non-toxic under normal use conditions. Despite these advantages, the field of long-acting antimicrobial coatings like MAP-1 remains under active research (Figure 2). Challenges such as material

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scalability, regulatory approval, and comprehensive in vivo testing continue to shape the pathway to global adoption [4].

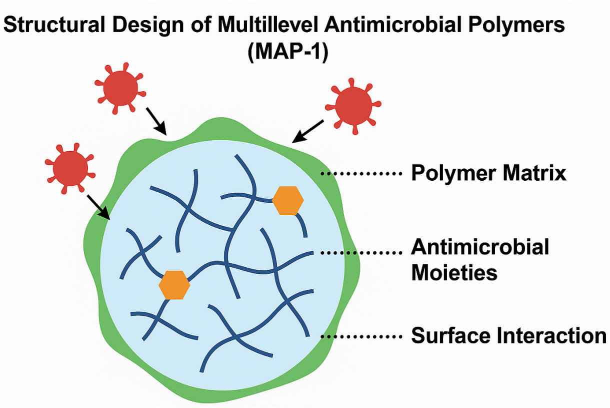

Figure 2. Structural design of antimicrobial action of MAP-1 coating.

This review aims to summarize the current understanding of MAP-1 technology, outline its chemical and functional properties, assess its real-world applications and antimicrobial efficacy, compare it to existing antimicrobial coating technologies, and highlight future directions for innovation and deployment [4,5].

Chemistry and Mechanism of MAP-1

Multilevel Antimicrobial Polymer-1 (MAP-1) represents a novel antimicrobial coating system developed to combat microbial threats on a variety of surfaces using a multilevel approach. At its core, MAP-1 integrates a chemically robust polymeric matrix with embedded antimicrobial agents, designed to function across multiple mechanisms to ensure both immediate and long-lasting protection. The base matrix is typically constructed using polyurethane, acrylic, or silicone-based polymers, chosen for their flexibility, adhesion, and environmental stability. These polymers form a thin, transparent coating layer that can adhere to metal, glass, ceramic, plastic, and even textile surfaces without altering their optical or mechanical properties [6].

The first layer of defense offered by MAP-1 is its contact-killing mechanism. Embedded within the polymer matrix are quaternary ammonium compounds (QACs), which are covalently bonded to prevent leaching. These positively charged groups interact with the negatively charged cell membranes of bacterial and viral envelopes, leading to membrane disruption, leakage of intracellular contents, and subsequent cell death. Because these agents are fixed to the surface, the antimicrobial activity remains effective for extended periods without posing environmental hazards through chemical release [7].

In addition to contact-killing, MAP-1 is engineered to exhibit anti-adhesion properties that prevent microbial settlement in the first place. This is achieved through surface modifications that alter the hydrophilicity and surface energy of the coating, creating an environment where microbial cells find it difficult to adhere. Some formulations also incorporate micro- or nanoscale texturing, mimicking naturally antimicrobial surfaces such as shark skin, to physically discourage microbial colonization and biofilm formation [8].

Another significant antimicrobial mechanism is the sustained release of biocidal compounds. While some active components are immobilized, others such as encapsulated disinfectants or reactive oxygen species (ROS)-generating agents are slowly released over time, offering secondary antimicrobial protection. This time-dependent release ensures ongoing disinfection between cleanings or reapplications, making it highly suitable for high-touch surfaces in public or clinical settings [8,9].

From a chemical standpoint, MAP-1 coatings undergo crosslinking reactions during curing, often triggered by UV exposure or thermal treatment. This crosslinking not only stabilizes the polymer structure but also entraps the active agents uniformly throughout the matrix. Advanced fabrication techniques, such as sol-gel processing and emulsion polymerization, have been used to ensure a homogenous dispersion of antimicrobial agents, while preserving the mechanical integrity and transparency of the coating [6,10].

An important advantage of MAP-1 is its optical clarity and biocompatibility, which allows it to be applied on consumer-facing surfaces like touchscreen devices or medical instruments. Unlike traditional metal-based coatings, MAP-1 does not discolor or degrade over time and has shown no cytotoxic effects in ISO-certified biocompatibility tests. Furthermore, it is odorless, non-irritating to skin, and safe for indoor use, making it suitable for applications ranging from hospital surfaces and elevators to public transport and school environments [11].

Overall, the chemical composition and multilevel mechanism of MAP-1 coatings combine to offer a highly effective, durable, and user-friendly antimicrobial solution. By integrating both physical and chemical strategies into one surface coating, MAP-1 represents a major advancement in the fight against surface-borne microbial transmission [11].

Application Areas of MAP-1

The versatility and effectiveness of Multilevel Antimicrobial Polymer-1 (MAP-1) have enabled its application across a wide range of public and private domains. As a transparent, durable, and biocompatible antimicrobial coating, MAP-1 has been deployed in environments with high microbial load and frequent human contact. One of the most prominent application areas is healthcare infrastructure, including hospitals, clinics, diagnostic laboratories, and long-term care facilities. In these settings, surfaces such as bed rails, doorknobs, medical carts, and monitor screens are common vectors for microbial transmission. MAP-1 coatings have demonstrated the ability to reduce microbial surface contamination significantly, contributing to the prevention of healthcare-associated infections (HAIs). The coating's long-lasting activity reportedly effective for up to 90 days also reduces the frequency of manual disinfection and associated labour costs [12].

Another key sector benefiting from MAP-1 technology is public transportation. In response to rising hygiene concerns during and after the COVID-19 pandemic, buses, trains, elevators, and airport terminals have increasingly adopted antimicrobial coatings on handrails, buttons, seatbacks, and touchscreens. MAP-1 is well-suited for such uses due to its

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strong adhesion to metal, glass, and plastic surfaces and its ability to maintain transparency, ensuring it does not alter the appearance or usability of controls and displays. Moreover, its non-toxic formulation makes it safe for daily exposure by commuters of all ages [13]. Educational institutions have also adopted MAP-1 coatings to enhance hygiene in classrooms, libraries, computer labs, and cafeterias. High-touch surfaces like desks, chairs, whiteboards, and keyboards are treated with the coating to mitigate microbial spread among students. Because the coating is odourless, non-irritating, and free from heavy metals or formaldehyde, it complies with indoor air quality regulations and child safety standards, making it particularly suitable for school and daycare environments [12,13].

In the textile industry, MAP-1 has been applied to uniforms, curtains, upholstery, and face masks. Using a sprayable or dip-coating process, the polymer forms a flexible, invisible layer that retains antimicrobial functionality even after multiple wash cycles. This application is especially valuable in hospital linens, hotel bedding, and public seating fabrics. Independent studies have confirmed the antimicrobial efficacy of MAP-1 on textiles against a wide spectrum of pathogens, including Staphylococcus aureus, Escherichia coli, and enveloped viruses such as influenza [14].

Long-term field performance and safety data have also shown promising results. According to public reports and independent lab testing, MAP-1 coatings can retain more than 95% of their antimicrobial effectiveness even after three months of exposure to varying temperature and humidity conditions. Additionally, surface integrity is not compromised, with no observed peeling, yellowing, or degradation. ISO 21702 and ASTM E2180 tests confirm the sustained antimicrobial activity, while cytotoxicity and skin sensitivity assessments verify its biocompatibility [15].

Therefore, the broad surface compatibility, long-lasting protection, and proven safety of MAP-1 have enabled its widespread use in critical public sectors. As hygiene awareness increases globally, MAP-1 presents a reliable and sustainable solution for maintaining cleaner environments in high-contact zones [15,16].

Antimicrobial Efficacy and Testing Protocols

The antimicrobial efficacy of Multilevel Antimicrobial Polymer-1 (MAP-1) has been rigorously evaluated through both in vitro and in situ field testing. These evaluations are crucial for validating the real-world performance of MAP-1 across different pathogens and under varying environmental conditions. The efficacy of MAP-1 is primarily attributed to its multilevel mechanism that disrupts microbial cell membranes, inhibits biofilm formation, and neutralizes viral envelopes. To demonstrate and quantify these effects, standardized protocols are employed, most notably those outlined by ISO 22196, ISO 21702, and ASTM E2180 [17].

In in vitro laboratory tests, MAP-1-coated surfaces are typically inoculated with a defined microbial load of bacterial or viral strains, such as Escherichia coli, Staphylococcus aureus, and Pseudomonas aeruginosa for bacteria, and influenza or human coronavirus strains for viruses. The surfaces are then incubated for 24 hours under controlled humidity and temperature. Using ISO 22196, the bacterial reduction rate is calculated by comparing colony-forming units (CFUs) on coated versus uncoated surfaces. MAP-1 has consistently demonstrated microbial reductions exceeding 99.9% within 24 hours, with sustained efficacy over weeks or even months [18].

For viral efficacy, ISO 21702 is the standard testing protocol. Here, virus-laden suspensions are applied to the coated surfaces and assessed for viral titters using plaque assays or qPCR after a specified contact time. Studies have shown that MAP-1 can inactivate up to 99.99% of enveloped viruses, such as H1N1 and SARS-CoV-2, within 1–2 hours of exposure, supporting its use in high-touch and high-risk environments. The polymer's broad-spectrum action against bacteria, fungi, and viruses highlights its potential in comprehensive hygiene solutions [19].

To evaluate fungicidal activity, ASTM G21 and ASTM E2180 are commonly used. These tests involve inoculating surfaces with fungal spores such as Aspergillus niger or Candida albicans, followed by incubation and analysis of growth inhibition zones or CFU reduction. MAP-1 has demonstrated strong fungistatic and fungicidal activity, with inhibition rates surpassing 95%, making it suitable for applications where fungal contamination is a concern, such as HVAC systems or humid public facilities [20].

In addition to laboratory conditions, real-world field trials have been conducted to assess durability and efficacy over time. Surfaces in public buses, hospital wards, and school classrooms coated with MAP-1 were periodically swabbed and analysed for microbial contamination. These field tests, conducted over periods of 30 to 90 days, confirmed that microbial loads remained consistently low, validating the coating's long-lasting efficacy under routine usage and environmental exposure [21]. Importantly, MAP-1 efficacy evaluations are also supported by biocompatibility and toxicity testing in line with OECD guidelines and ISO 10993, ensuring that the antimicrobial effect does not compromise human or environmental safety. These tests confirm that MAP-1 is non-cytotoxic, non-sensitizing, and safe for skin contact, which is critical for public and medical use. In conclusion, the proven antimicrobial efficacy of MAP-1, supported by globally recognized standards and thorough testing protocols, reinforces its value as a high-performance, safe, and long-lasting antimicrobial solution for diverse applications [22].

Advantages and Limitations

Multilevel Antimicrobial Polymer-1 (MAP-1) offers a multifaceted solution to surface disinfection and pathogen control, positioning it as a next-generation material in the fight against infectious diseases. One of its most significant advantages is its broad-spectrum antimicrobial efficacy, which includes activity against bacteria (both Gram-positive and Gram-negative), viruses (including enveloped viruses like SARS-CoV-2), and fungi. This wide coverage is due to MAP-1's engineered surface chemistry, which disrupts microbial membranes and viral envelopes, providing both immediate and long-lasting protection [23].

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Another notable strength of MAP-1 lies in its durability and residual activity. Unlike conventional disinfectants that evaporate or degrade quickly, MAP-1 forms a stable, non-volatile coating that retains antimicrobial efficacy for several weeks, and in some cases, up to 90 days. This makes it particularly well-suited for use in high-touch, high-traffic environments such as hospitals, schools, public transport, and commercial buildings. Furthermore, compatibility with a wide range of surfaces including glass, metal, plastic, fabric, and painted walls expands its versatility across industries [24].

The biocompatibility and low toxicity of MAP-1 are also key advantages. Safety evaluations based on international standards (e.g., ISO 10993, OECD) have shown that the coating is non-irritating to skin, non-sensitizing, and safe for direct human contact. This makes MAP-1 ideal for environments frequented by vulnerable populations, including children and immunocompromised individuals. Despite these benefits, several limitations constrain the broader adoption of MAP-1. A primary challenge is scalability of production. The synthesis of complex antimicrobial polymers like MAP-1 can be resource-intensive and may require specialized facilities, limiting rapid deployment at scale. Furthermore, cost factors associated with large-scale application and maintenance may hinder its adoption, especially in low-resource settings [25].

Another concern is the potential for microbial resistance development. While MAP-1's multilevel mechanisms reduce this risk compared to single-mode disinfectants, prolonged and indiscriminate use may still contribute to adaptive resistance over time, warranting careful usage strategies and monitoring [26].

Finally, regulatory hurdles present a significant barrier. Antimicrobial coatings fall under stringent regulations in many jurisdictions, requiring comprehensive safety and efficacy testing for approval. These processes can be time-consuming and costly, slowing innovation and market access. In summary, while MAP-1 presents a robust antimicrobial solution with numerous advantages, addressing its limitations through innovation, cost-reduction strategies, and regulatory support will be key to its successful global implementation [27].

Comparison with Other Antimicrobial Coatings

Multilevel Antimicrobial Polymers (MAP-1) distinguish themselves from traditional antimicrobial coatings through their multistage defense mechanism, offering prolonged protection and broader efficacy against pathogens. However, for a comprehensive assessment, it's crucial to compare MAP-1 with other widely used coatings such as silver-based, copper-based, and photodynamic coatings [28].

Silver-based antimicrobial coatings operate via ion release mechanisms that disrupt microbial cell walls and interfere with enzyme activity. They are widely used due to their potent antimicrobial efficacy, but concerns remain regarding cytotoxicity, environmental persistence, and microbial resistance with prolonged use. Copper-based coatings offer similar benefits with slightly lower costs, especially in high-touch public applications, though they often require frequent polishing and lose efficacy over time due to oxidation [29].

Photodynamic coatings work by producing reactive oxygen species (ROS) upon exposure to light, thereby killing microorganisms. While highly effective in laboratory conditions, their performance in ambient light and real-world conditions is less consistent. Furthermore, their use is often limited to surfaces with constant light exposure [30].

In contrast, MAP-1 presents a hybridized system with both physical and chemical microbicidal properties. It offers long-lasting activity across a variety of surfaces, including plastic, glass, fabric, and metal, with reduced environmental and health risks due to its low toxicity formulation. (Table 1) [31].

Table 1. Comparison of MAP-1 with other antimicrobial coating technologies.

Feature	MAP-1	Silver-Based Coating	Copper-Based Coating	Photodynamic Coating
Antimicrobial Mechanism	Multi-mechanistic	Ion release	Contact killing	Light-activated ROS
Durability	High (7–90 days)	Moderate	Moderate	Low–moderate
Cost-effectiveness	High	Moderate–High	High	Moderate
Environmental Impact	Low (non-toxic)	Potential lion leaching	Medium (oxidation)	Dependent on dye used
Regulatory Approval	In progress (Asia)	Approved (some regions)	Approved	Limited

Future Perspectives

The evolution of Multilevel Antimicrobial Polymers (MAP-1) marks a significant advancement in surface hygiene and long-term infection control. Looking ahead, next-generation MAP materials are likely to incorporate responsive or stimuli-based mechanisms such as temperature, pH, or microbial-triggered activation to enhance precision and efficacy. These smart coatings could allow antimicrobial action only when needed, reducing overexposure and mitigating resistance development [32].

Integration with smart sensors and Internet of Things (IoT) platforms may further allow for real-time surface monitoring and reactivation signals, paving the way for dynamic and adaptive antimicrobial surfaces in healthcare, transportation, and consumer environments. Additionally, AI-driven formulation optimization is expected to accelerate material discovery and custom-fit polymers for specific environmental or microbiological challenges [33].

Another promising frontier is the strategic role of MAP coatings in curbing antimicrobial resistance (AMR). By offering

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broad-spectrum activity without relying solely on antibiotics or biocides, MAP-1 coatings can reduce the microbial load and limit the selection pressure that often leads to resistance. These innovations, combined with scalable synthesis and eco-conscious design, hold the potential to redefine global hygiene standards, making MAP-1 not just a product, but a platform for future antimicrobial technology [34].

Conclusions

Multilevel Antimicrobial Polymers (MAP-1) represent a breakthrough in sustainable surface disinfection, offering durable, broad-spectrum protection across diverse materials and environments. By combining physical and chemical antimicrobial mechanisms, MAP-1 addresses limitations of conventional coatings and aligns with long-term pathogen control goals. Its successful application in public infrastructure and healthcare settings highlights both its efficacy and safety. As research advances, the integration of smart functionalities and data-driven design holds promise to expand its impact further. MAP-1 is poised to become a cornerstone technology in the global fight against infectious diseases and antimicrobial resistance, supporting cleaner and safer public spaces.

Disclosure statement

No potential conflict of interest was reported by the authors.

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