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A Mini Review of Microbiological Factors on Surfaces Associated with Infection Transmission and Microbial Biofilms

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Abstract

The transfer of harmful microorganisms via environmental surfaces, particularly in hospitals and healthcare environments, is a crucial factor in the dissemination of acquired infections that pose significant risks to public health. This review article explores the microbiological aspects of surfaces, the elements that influence the establishment and growth of microbes, along with the function of microbial biofilms as resilient and stable substrates. Biofilms are intricate multicellular structures supported by matrices of polysaccharides, proteins, and nucleic acids, which enhance the resistance of microbes to both antibiotics and disinfectants. An in-depth analysis of the molecular processes involved in biofilm formation, including quorum sensing mechanisms, regulation of gene expression related to extracellular polymer production (EPS) , and cellular interactions, constitutes a significant component of this article. Additionally, the impact of environmental factors such as humidity, surface characteristics, and temperature on the stability of the surface microbiome is examined. Following this, innovative biological and nanobiotechnological approaches for the swift detection and elimination of biofilms are presented, including the application of antimicrobial nanoparticles, bioactive coatings, and strategies involving drug combinations, which can play a vital role in preventing the spread of drug-resistant infections. Furthermore, strategies for management and prevention are suggested to control the microbial load on surfaces and diminish the occurrence of infectious diseases within healthcare settings. This review article aims to aid in the development of more effective methods for managing surface-associated infections and opens new avenues in the realm of environmental and medical biotechnology.

Key words: Microorganism transmission, Environmental surfaces, Surface microbiome, Nanobiotechnology, Quorum sensing

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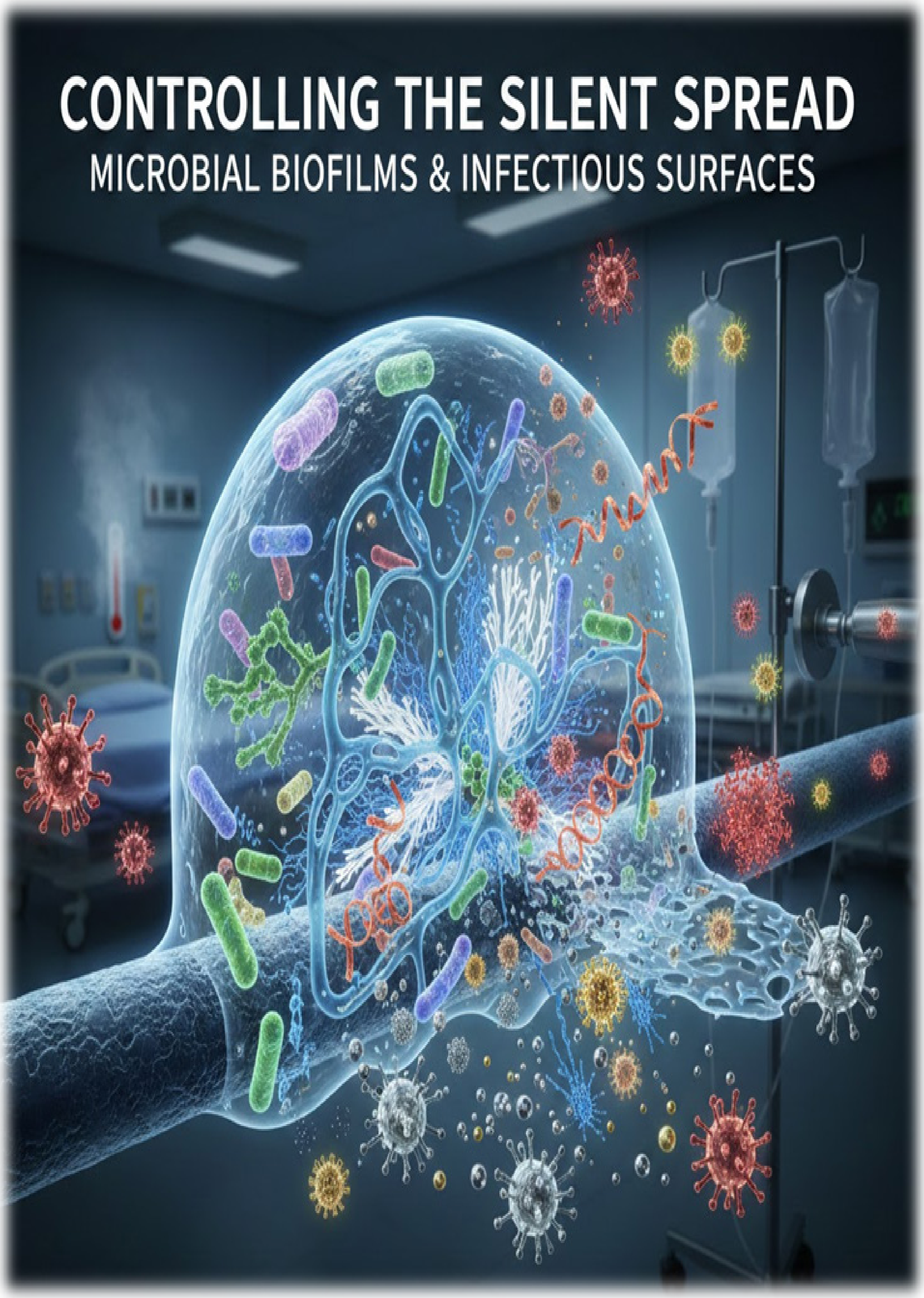
Graphical Abstract



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Introduction

The transmission of infectious agents through contaminated surfaces, commonly referred to as fomites, represents a persistent and significant challenge in healthcare settings, public environments, and food-processing industries(Castaño et al., 2021). High-touch surfaces such as medical devices, door handles, countertops, and packaging materials can act as reservoirs for pathogenic microorganisms, facilitating indirect transmission to humans. Despite routine cleaning and disinfection practices, outbreaks associated with surface-mediated transmission continue to occur, underscoring the need for a deeper understanding of microbial survival mechanisms on abiotic surfaces.A wide range of pathogenic microorganisms, including Gram-positive and Gram-negative bacteria, fungi, and viruses, are capable of surviving on surfaces for extended periods. The duration of survival is influenced by multiple factors such as temperature, humidity, surface material, nutrient availability, and exposure to disinfectants. Importantly, many microorganisms adapt to hostile surface environments by altering their physiological state, allowing them to persist under conditions that would otherwise be lethal to planktonic cells(Wißmann et al., 2021). In natural and engineered environments, microorganisms rarely exist as isolated, free-living cells. Instead, they frequently form complex, surface-associated communities known as biofilms. Biofilms are structured aggregates of microbial cells embedded within a self-produced extracellular polymeric substance (EPS) matrix(Martín-Rodríguez, 2023). This matrix provides mechanical stability, mediates adhesion to surfaces, and offers protection against environmental stresses, including desiccation, ultraviolet radiation, and antimicrobial agents.The formation of biofilms on surfaces dramatically alters microbial behavior and survival(da Silva Araújo, 2014). Cells within biofilms exhibit altered gene expression profiles, reduced metabolic rates, and enhanced stress tolerance compared to their planktonic counterparts. These characteristics contribute to increased resistance to antibiotics and disinfectants, making biofilm-associated microorganisms particularly difficult to eradicate(Stewart et al., 2019).As a result, biofilms are recognized as a major contributor to chronic infections, hospital-acquired infections, and persistent contamination in industrial settings.From an infection control perspective, biofilms play a critical role in the persistence and transmission of pathogens via fomites(Kramer et al., 2024). Detachment of cells or biofilm fragments from contaminated surfaces can lead to secondary contamination of hands, equipment, or food products, thereby increasing the risk of infection spread. Understanding the microbiological and environmental factors that promote biofilm formation and stability on surfaces is therefore essential for developing effective prevention and control strategies(Muhammad et al., 2020; Tahir, 2017).This review aims to provide a comprehensive overview of the microbiological factors influencing microbial persistence on surfaces, with a particular emphasis on the role of biofilms in infection transmission. By examining current knowledge on biofilm formation, survival mechanisms, and resistance traits, this article seeks to highlight key challenges and identify potential approaches for mitigating surface-mediated transmission of infectious agents.

Microbial Survival on Surfaces

A wide variety of microorganisms are capable of contaminating abiotic surfaces, including bacteria, fungi, and viruses, each with distinct structural and physiological characteristics that influence their survival. Clinically important bacteria such as *Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa , Acinetobacter baumannii* are frequently isolated from contaminated surfaces, particularly in healthcare environments(Chaoui et al., 2019). In addition, fungal species including Candida spp. and Aspergillus spp. can persist on surfaces and contribute to opportunistic infections. Viruses such as influenza virus, norovirus, and coronaviruses are also able to remain infectious on surfaces for varying periods. Gram-positive bacteria generally exhibit longer survival on dry surfaces due to their thick peptidoglycan cell walls, whereas the persistence of viruses is strongly influenced by surface type, temperature, and humidity. These differences in survival strategies play a crucial role in surface-mediated transmission of infectious agents(Bonadonna et al., 2021).

Environmental Factors

Microbial persistence on surfaces is strongly affected by a range of environmental factors that regulate survival, growth, and biofilm development. Temperature and relative humidity are among the most influential parameters, as they directly impact microbial metabolism and structural stability(Stanaszek-Tomal, 2020). Higher humidity levels generally enhance the survival of Gram-negative bacteria by preventing desiccation, whereas low-humidity conditions may favor the persistence of certain viruses. Surface material also plays a critical role in microbial survival, with non-porous materials such as stainless steel, glass, and plastic often supporting longer persistence compared to porous surfaces like wood or fabric. The smoothness and chemical composition of surfaces influence microbial adhesion and resistance to cleaning procedures. In addition, the presence of nutrients on surfaces significantly enhances microbial persistence. Organic residues such as blood, mucus, or food particles can serve as nutrient sources, promoting microbial growth and facilitating biofilm formation. These environmental factors often act synergistically, creating favorable conditions for long-term microbial survival and increasing the risk of surface-mediated infection transmission(Wißmann et al., 2021).

Infection Transmission via Surfaces

Infection transmission via contaminated surfaces primarily occurs through indirect contact, most commonly involving hand contact with contaminated objects followed by self-inoculation of the eyes, nose, or mouth, or transfer to susceptible hosts(Rashid et al., 2017). In healthcare environments, high-touch surfaces such as bed rails, door handles, bedside tables, and medical devices serve as critical reservoirs for pathogenic microorganisms. These surfaces are frequently exposed to contamination and are often inadequately disinfected, allowing microorganisms to persist and spread within clinical settings. Consequently, surface-mediated transmission plays a significant role in the dissemination of infectious agents(Phan et al., 2025).

Surface contamination is closely linked to the occurrence of healthcare-associated infections (HAIs), which represent a major burden to healthcare systems worldwide. Pathogens, particularly multidrug-resistant organisms (MDROs), are capable of surviving on environmental surfaces for extended periods and can be readily transferred between patients, healthcare workers, and the surrounding environment(Paladini et al., 2025). This continuous cycle of contamination and transmission contributes to hospital outbreaks, prolonged hospital stays, increased morbidity and mortality, and elevated healthcare costs, highlighting the critical importance of effective surface decontamination and infection control strategies.

Microbial Biofilms on Surfaces

Microbial biofilms are highly organized communities of microorganisms that are attached to surfaces and embedded within a self-produced extracellular polymeric substance (EPS) matrix. This matrix is primarily composed of polysaccharides, proteins, lipids, and extracellular DNA, and plays a critical role in maintaining the structural integrity of the biofilm(Flemming & Wingender, 2010). The EPS matrix provides mechanical stability, facilitates adhesion to biotic and abiotic surfaces, and offers protection against environmental stressors such as desiccation, nutrient limitation, and exposure to antimicrobial agents. Biofilm formation is a dynamic and multistep process that typically begins with the initial, reversible adhesion of microbial cells to a surface. This is followed by irreversible attachment and the formation of microcolonies as cells proliferate and produce EPS. As the biofilm develops, it undergoes maturation, resulting in a complex three-dimensional structure with channels that allow the distribution of nutrients and removal of waste products(Donlan & Costerton, 2002). In the final stage, cells or clusters of cells disperse from the mature biofilm, enabling colonization of new surfaces and contributing to the spread of infection. Microorganisms residing within biofilms exhibit significantly increased resistance to disinfectants, antibiotics, and host immune defenses compared to planktonic cells.

This enhanced resistance arises from multiple mechanisms, including limited penetration of antimicrobial agents through the EPS matrix, altered metabolic and physiological states of biofilm-associated cells, and the presence of persister cells that are highly tolerant to antimicrobial treatments. As a result, biofilms represent a major challenge in infection control and are closely associated with persistent and recurrent infections(-Sauer et al., 2022).

Role of Biofilms in Infection Transmission

Biofilms formed on environmental surfaces and medical devices act as long-term reservoirs of pathogenic microorganisms, enabling their persistence despite routine cleaning and disinfection procedures(Donlan & Costerton, 2002). Cells and biofilm fragments released from these structured communities can readily contaminate hands, medical instruments, and fluids, facilitating both direct and indirect transmission to susceptible hosts. This continuous shedding of microorganisms contributes to the development of acute and chronic infections, particularly in healthcare settings. Biofilm-associated infections are notoriously difficult to eliminate due to their enhanced resistance to antimicrobial agents and host immune responses, and in many cases, effective control requires the removal or replacement of contaminated devices or surfaces, highlighting the critical role of biofilms in infection transmission(Krukiewicz et al., 2022).

Conclusion

Microbiological factors influencing microbial survival on surfaces play a crucial role in the transmission of infectious agents in both healthcare and community environments. The ability of microorganisms to persist on abiotic surfaces is strongly affected by their structural characteristics, environmental conditions, and interactions with surface materials. Among these factors, biofilm formation represents one of the most important survival strategies, as it significantly enhances microbial persistence, stress tolerance, and resistance to disinfectants, antibiotics, and host immune defenses. Biofilms on environmental surfaces and medical devices act as continuous sources of contamination, facilitating the spread of pathogens and contributing to healthcare-associated and community-acquired infections. Their presence complicates routine cleaning and disinfection procedures and increases the risk of recurrent and chronic infections. Therefore, a comprehensive understanding of surface microbiology, biofilm development, and resistance mechanisms is essential for improving infection prevention and control measures. Advancing surface decontamination technologies, implementing effective cleaning protocols, and developing anti-biofilm strategies are critical steps toward reducing infection transmission and improving public health outcomes.

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