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Bacterial Biofilms and Their Role in Antimicrobial Resistance – Mini-review

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Abstract: *Antimicrobial resistance remains a critical challenge in both human and veterinary medicine, with bacterial biofilms playing a central role in the persistence of chronic and recurrent infections. Biofilms are complex microbial communities embedded in a self-produced extracellular matrix that enhances bacterial survival under antimicrobial pressure and host immune responses. This mini-review synthesizes current evidence on the contribution of biofilms to reduced antimicrobial efficacy and their clinical relevance, particularly in veterinary practice.*

Literature analysis indicates that bacteria within biofilms can exhibit up to 10–1000 times higher tolerance to antimicrobial agents compared to their planktonic counterparts. This increased tolerance is driven by multiple mechanisms, including limited drug penetration through the extracellular matrix, altered microenvironmental conditions, reduced metabolic activity, and the presence of persister cells. In addition, horizontal gene transfer within biofilm structures facilitates the spread of resistance determinants among bacterial populations.

Clinically relevant biofilm-forming organisms include Staphylococcus pseudintermedius, Escherichia coli, Pseudomonas aeruginosa, and Staphylococcus aureus, which are frequently associated with chronic infections such as otitis, dermatitis, urinary tract infections, and device-related infections in animals. These conditions are often characterized by therapeutic failure, recurrence, and the need for prolonged treatment strategies.

Overall, biofilm-associated infections represent a major obstacle in effective antimicrobial therapy. A better understanding of their biology is essential for improving diagnostic approaches and developing targeted therapeutic strategies within a One Health framework.

• Introduction

Antimicrobial resistance (AMR) represents a major global challenge, affecting both human and veterinary medicine [Tang et al., 2023, Velazquez-Meza et al., 2022; Ifedinezi et al., 2024, Monteiro et al., 2025, Popa et al., 2025, Iancu et al., 2025, Popa et al., 2025, Herman et al., 2012, Irfan et al., 2022]. The increasing and sometimes inappropriate use of antibiotics has contributed to the selection of microorganisms capable of developing complex resistance mechanisms. In this context, bacterial biofilms are recognized as a key factor in the persistence of infections and the reduced effectiveness of antimicrobial treatments. Furthermore, biofilms contribute to AMR not only through physical protection, but also through physiological and genetic adaptations, including reduced metabolic activity, horizontal gene transfer, and the presence of persister cells that exhibit transient antibiotic tolerance [Pallee et al., 2023].

Biofilms are structured communities of microorganisms that adhere to biological or abiotic surfaces and are embedded in a protective extracellular matrix. This organization provides significant adaptive advantages, including protection against antibiotics and the host immune system. In veterinary medicine, biofilms are frequently involved in chronic infections such as otitis, skin infections, and urinary tract infections, making them highly relevant in clinical practice [Zafer et al., 2024].

The extracellular matrix is mainly composed of polysaccharides, proteins, lipids, and extracellular DNA, which collectively enhance structural stability and contribute to antimicrobial penetration barriers. Additionally, quorum sensing plays a crucial role in regulating biofilm development and coordinating bacterial behavior within the community [Karygianni et al., 2020].

Additionally, biofilms are increasingly recognized as dynamic and heterogeneous systems rather than static structures, with gradients of oxygen, nutrients, and metabolic activity influencing bacterial behavior. Their formation follows distinct stages (initial adhesion, microcolony formation, maturation, and dispersion), each contributing differently to antimicrobial tolerance. The global burden of biofilm-associated infections is substantial, as they are estimated to be involved in the majority of chronic and device-related infections, highlighting their clinical and epidemiological importance [Muhammad et al., 2020].

Biofilm-associated infections are particularly difficult to eradicate due to their ability to evade both innate and adaptive immune responses, often leading to recurrent or long-term infections. This has significant implications for One Health, as biofilm-related pathogens can circulate between animals, humans, and the environment. Furthermore, emerging research highlights the need for novel therapeutic strategies, including quorum sensing inhibitors, enzymatic matrix disruption, and nanoparticle-based antimicrobial delivery systems [Del Pozo et al., 2018].

• Material and method

This study represents a mini-review conducted through the analysis of scientific literature available in international databases such as PubMed, ScienceDirect, and Google Scholar. Articles published primarily within the last 10–15 years and relevant to bacterial biofilms and antimicrobial resistance were selected.

The literature search was performed using a combination of predefined keywords and Boolean operators, ensuring broad coverage of relevant studies while maintaining focus on biofilm-associated antimicrobial resistance. Duplicate records were removed, and abstracts were screened prior to full-text evaluation.

Inclusion criteria targeted both review articles and experimental studies addressing biofilm formation, resistance mechanisms, and their implications in veterinary medicine. The keywords used for literature search included: "biofilm," "antimicrobial resistance," "veterinary infections," "bacterial biofilms," and "chronic infections."

Studies were included if they provided clear experimental data or comprehensive syntheses related to biofilm biology, antimicrobial resistance mechanisms, or clinical relevance in veterinary and/or human medicine. Articles not available in English or lacking sufficient methodological detail were excluded from analysis.

However, the methodology is limited by the narrative nature of the review, which may introduce selection bias due to the absence of a systematic screening protocol (e.g., PRISMA framework). Additionally, variability in study designs across the included literature may affect comparability of results. Another limitation includes the potential for publication bias, as studies reporting significant findings are more likely to be published. Furthermore, the lack of standardized data extraction procedures may influence the consistency of the synthesized information across sources.

• Results and discussions

The analysis of the selected studies indicates that biofilms are involved in a significant proportion of chronic infections. Bacteria organized in biofilms exhibit increased tolerance to antibiotics, up to 10–1000 times higher compared to their planktonic counterparts [Pallee et al., 2023].

This increased tolerance is multifactorial, involving restricted antibiotic penetration, altered microenvironmental conditions within the biofilm, and the presence of slow-growing or dormant bacterial subpopulations that are inherently less susceptible to antimicrobial agents [Liu et al., 2024].

Among the most frequently involved microorganisms are *Staphylococcus pseudintermedius*, associated with skin and ear infections in dogs, and *Escherichia coli*, commonly implicated in urinary tract infections. These species demonstrate a high capacity to form stable biofilms [Singh et al., 2013; Kern et al., 2018].

Other clinically relevant biofilm-forming pathogens reported in the literature include *Pseudomonas aeruginosa* and *Staphylococcus aureus*, both of which are strongly associated with persistent and device-related infections in both veterinary and human medicine [Tuon et al., 2022; Popa et al., 2026, Theis et al., 2023].

Biofilm formation is a complex process that begins with the reversible adhesion of bacteria to a surface, followed by irreversible attachment and production of an extracellular matrix. This matrix consists of polysaccharides, proteins, and extracellular DNA, providing structural stability and protection. Initial adhesion is often mediated by bacterial surface structures such as pili, fimbriae, and adhesins, which facilitate attachment to host tissues or abiotic surfaces such as medical devices [Muhammad et al., 2020].

The increased resistance of biofilms is due to several factors. The extracellular matrix limits antibiotic diffusion, reducing their effective concentration at the bacterial level. Furthermore, the reduced metabolic activity of cells within the biofilm makes them less susceptible to antibiotics targeting active cellular processes [Clayton et al., 2017].

In addition, gradients in oxygen and nutrient availability lead to metabolic heterogeneity, which further reduces the efficacy of antibiotics that rely on active bacterial growth [Stokes et al., 2019].

Persister cells play a crucial role in bacterial survival under stress conditions, including antibiotic exposure [Fisher et al., 2017]. Additionally, the high bacterial density facilitates the transfer of resistance genes. These persister populations are phenotypically tolerant rather than genetically resistant, allowing them to survive treatment and repopulate the biofilm once antibiotic pressure is removed [Fisher et al., 2017, Lewis et al., 2012].

Biofilms are involved in numerous veterinary conditions, including otitis externa, dermatitis, urinary tract infections, and infections associated with medical implants. These infections are often chronic and difficult to treat, requiring complex therapeutic approaches. They are particularly problematic in animals with underlying conditions such as immunosuppression, skin barrier defects, or prolonged antimicrobial exposure [Nesse et al., 2023].

The presence of biofilms contributes to infection recurrence and treatment failure, highlighting the importance of proper identification and management in veterinary practice. Accurate diagnosis often requires advanced techniques such as molecular methods or imaging approaches, as standard culture techniques may underestimate biofilm involvement [Lewis et al., 2012].

Additionally, biofilm-related infections in veterinary patients can significantly increase treatment costs and duration, as well as reduce animal welfare and productivity. Companion animals and livestock may serve as reservoirs for resistant biofilm-forming bacteria, raising concerns about zoonotic transmission and public health impact.

This interconnection between animal health and human health underscores the importance of a One Health approach in addressing biofilm-associated antimicrobial resistance [Elbehiry et al., 2025].

• Conclusions

Bacterial biofilms represent a major factor in the development of antimicrobial resistance and the persistence of infections. Their ability to protect bacteria from antibiotics and facilitate gene transfer highlights their clinical importance.

They act as a critical evolutionary platform for bacterial adaptation, significantly accelerating the emergence and dissemination of resistant strains.

In veterinary medicine, understanding biofilm mechanisms is essential for improving therapeutic strategies and reducing the impact of antimicrobial resistance. The development of innovative treatment methods remains an important direction for future research.

Future perspectives should also focus on improved diagnostic tools and preventive strategies to limit biofilm establishment at early stages of infection.

Overall, integrating biofilm-targeted strategies into routine veterinary practice, along with prudent antibiotic use, is crucial for mitigating the growing burden of antimicrobial resistance at both clinical and population levels.

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