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Polysaccharide-Rich Biofilms in Pathogenic Microorganisms: Molecular Architecture, Functional Roles, and Innovative Therapeutic Strategies

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ABSTRACT

Microbial biofilms are complex communities of microorganisms attached to surfaces and surrounded by an extracellular matrix made up of polysaccharides, proteins, and other biopolymers, which contribute to their structural stability and function. Polysaccharides play a central role in biofilm formation, providing adhesion, cohesion, and protection against environmental stress, antibiotics, and host immune defenses. This review explores the biosynthesis and molecular diversity of microbial exopolysaccharides (EPS), focusing on their functional roles in biofilm architecture and pathogenicity. It discusses the different biosynthetic pathways that produce EPS, such as the Wzx/Wzy-dependent, ABC transporter-dependent, and synthase-dependent pathways. The review also highlights the structural diversity of key polysaccharides like alginate, Psl, Pel, and PNAG, and their contribution to biofilm stability and antibiotic resistance. Additionally, emerging therapeutic strategies targeting the biofilm matrix, including enzymatic degradation, antibiofilm agents, and quorum sensing inhibition, are explored as potential approaches to combat biofilm-associated infections. These strategies aim to disrupt the EPS matrix, enhance antibiotic penetration, and improve infection control, especially in chronic and multidrug-

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resistant infections caused by pathogens like Pseudomonas aeruginosa and Staphylococcus aureus.

Keywords
Biofilm, Polysaccharides, Exopolysaccharides, Biosynthesis, Antibiotic Resistance, Quorum Sensing, Therapeutic Strategies, Microbial Infections

Introduction

Microbial biofilms are defined as structured communities of microorganisms irreversibly attached to a surface surrounded by a self-produced matrix of extracellular polymeric substances (EPS). The matrix of this complex system is mostly composed of polysaccharides, proteins, nucleic acids and lipids which together are termed the 'matrixome' due to their broad biochemical and functional roles in biofilm architecture and physiology [1-3]. Biofilms are ubiquitous in natural, industrial and clinical environments and are of great importance in understanding the survival, persistence and resistance to environmental stresses and antimicrobial agents of microbes [4].

The EPS matrix is composed of polysaccharides that act as important scaffolds that provide mechanical stability, adhesion, cohesion and protection against host immune defenses and antibiotic penetration [5]. Most of these biopolymers are remarkably structurally diverse, from homopolysaccharides like bacterial cellulose to heteropolysaccharides like alginate, Psl, Pel and polysaccharide intercellular adhesin (PIA/PNAG) which are synthesized by distinct biosynthetic pathways and play species specific functional roles [6].

Biofilm associated infections are a major clinical challenge because they are recalcitrant to conventional therapies and contribute to chronic and device associated infections. Polysaccharide rich biofilms produced by P. aeruginosa, S. aureus, Klebsiella pneumoniae and fungal pathogens like Candida albicans enhance persistence of colonization and antimicrobial tolerance and exacerbate disease severity and treatment [7, 8]. In addition, polymicrobial biofilms have synergistic interactions that increase biofilm robustness and pathogenicity which cannot be addressed by single target therapies [3, 9].

Polysaccharides play a critical role in biofilm formation and maintenance and given this, there is increasing interest in the molecular structure, biosynthesis and functional mechanisms of polysaccharides in order to discover innovative approaches to disrupt biofilms and combat antimicrobial resistance. In this review, the molecular architecture as well as functional roles of polysaccharide-rich biofilms of pathogenic microorganisms are comprehensively reviewed and emerging therapeutic strategies to target the biofilm matrix for effective infection control are explored [10].

Biosynthesis and Molecular Diversity of Microbial Exopolysaccharides

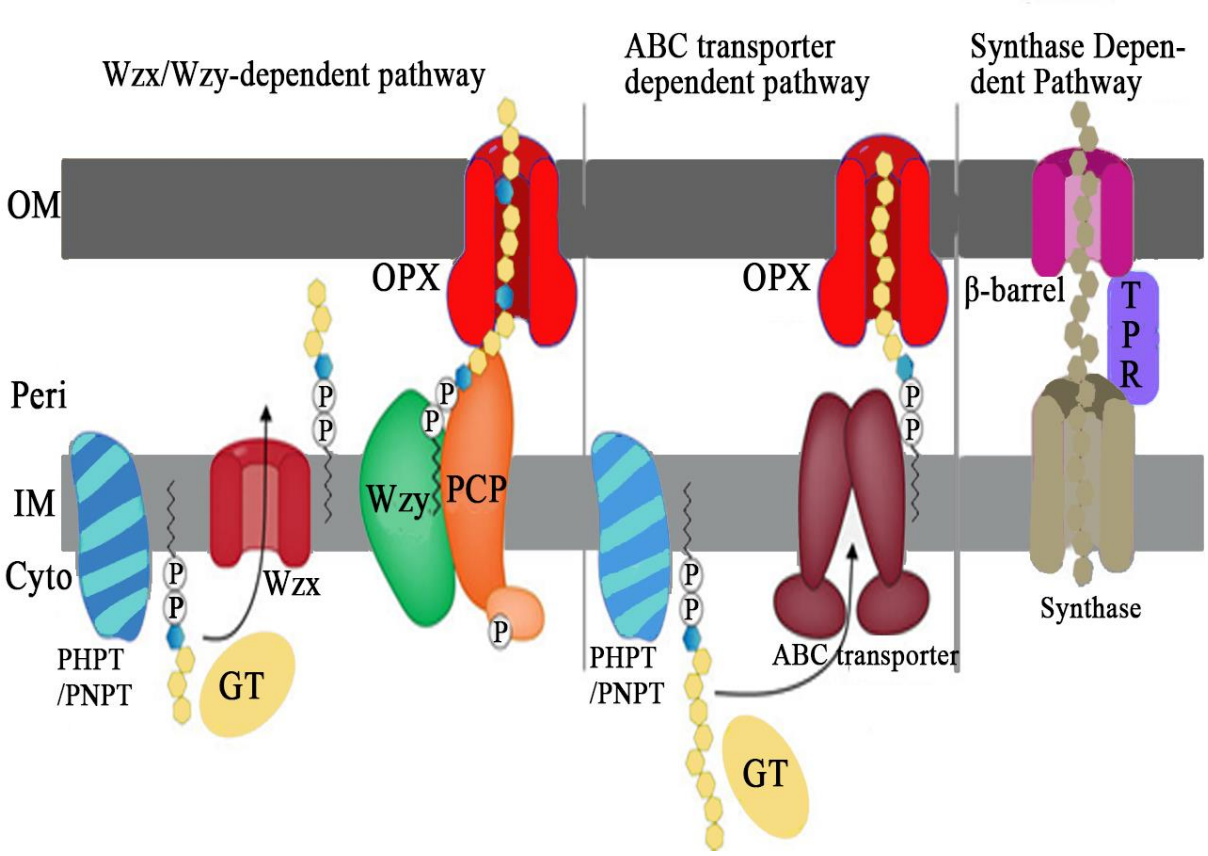
Biosynthetic Pathways of Microbial Exopolysaccharides

Exopolysaccharides (EPS) are produced by microbes via complex biosynthetic pathways which yield the chemical composition, molecular weight and functional properties of the EPS. Bacteria have been found to produce the biosynthetic routes of Wzx/Wzy-dependent pathway, ABC transporter-dependent pathway, synthase-

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dependent pathway and extracellular synthesis (Figure 1).



Wzx/Wzy-dependent pathway: Polymerization of repeat oligosaccharide units at the inner membrane, translocation across the membrane by the Wzx flippase and polymerization by the Wzy polymerase characterize the Wzx/Wzy-dependent pathway. It is often involved in heteropolysaccharide biosynthesis including Psl and Pel polysaccharides from P. aeruginosa [11, 12].

The ABC transporter dependent pathway: This is a process where the polysaccharide chain is assembled in the cytoplasm and then exported in a single step across both the inner and outer membranes by ATP binding cassette (ABC) transporters. The pathway described is often followed by capsular polysaccharides in S. aureus and Escherichia coli [13, 14].

Synthase Dependent Pathway: This pathway is unique in that it couples polymerization and translocation through a single integral membrane enzyme and it produces polysaccharides like bacterial cellulose and alginate. For instance, membrane associated alginate synthase complex of P. aeruginosa is tightly regulated in response to environmental cues and host conditions to synthesize alginate [12, 15].
Some homopolysaccharides such as dextran and curdlan, are synthesized extracellularly by the secretion of enzymes into the environment. As this extracellular

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polymerization allows direct modification of polysaccharide structure outside the cell [16].

Molecular Architecture and Analytical Characterization of Biofilm Polysaccharides

Chemical Composition and Structural Motifs of Key Polysaccharides

Polysaccharides of biofilm are highly chemically diverse and structurally distinct from each other and play an important role in biofilm stability, functionality and microbial virulence. Alginate, Psl, Pel, poly-β-1,6-N-acetylglucosamine (PNAG) and cellulose have been among the most extensively studied polysaccharides with respect to monosaccharide building blocks and linkage patterns.

Alginate is an anionic heteropolysaccharide containing mainly residues of β-D-mannuronic acid (M) and α-L-guluronic acid (G) arranged in different sequences of the sequential homopolymeric M-blocks and G-blocks and MG-blocks. It is made particularly by P. aeruginosa mucoid strains, where it assists with biofilm hydration, immune evasion and antibiotic obstruction because of its creation of a sticky and defensive framework [17]. Another major component in P. aeruginosa is Psl polysaccharide which is a neutral polysaccharide composed of repeating pentasaccharide units of D-mannose, D-glucose and L-rhamnose. However, it mainly serves as a means of low energy surface adhesion and intercellular interaction at the early biofilm formation stages [18]. In addition, Pel, a glucose rich cationic polysaccharide also produced by P. aeruginosa which supports biofilm structural integrity and promotes antibiotic tolerance should compensate if Psl production is deficient [19].

PNAG (polysaccharide intercellular adhesin) or poly-β-1,6-N-acetylglucosamine, is a homopolysaccharide consisting of β-1,6-linked N-acetylglucosamine residues. S. aureus and E. coli intercellular adhesion and protection from host immune responses and antimicrobial agents are facilitated by it and is a critical biofilm matrix component [20]. It also consists of cellulose, a linear β-1,4-glucan which is produced in various bacteria like Agrobacterium and Gluconacetobacter. The scaffold for biofilm matrix assembly and for adhesion to biotic and abiotic surfaces [21].

State of the art analytical techniques for the characterization of the polysaccharides of biofilms

Biofilm polysaccharides functionally fulfill important roles and their accurate characterization at molecular and structural levels is fundamental to the understanding of these roles and in the design of targeted interventions. It usually consists of a combination of advanced analytical techniques:

Nuclear Magnetic Resonance (NMR) Spectroscopy: A method that gives detailed information on monosaccharide composition, glycosidic linkages and polymer conformation. Solution state and solid state NMR are both very useful for fine structural details of EPS components.

Fourier-Transform Infrared (FTIR) Spectroscopy: This method presents the ability to identify functional groups that are chemical bonds of polysaccharides such as

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hydroxyl, carboxyl and amide groups that are useful to differentiate EPS types.

Hydrolysis followed by chromatography (HPLC, GC-MS): used for monosaccharide composition analysis (determination of sugar types, ratios and derivatization profiles) used for detailed characterization [22, 23].

Microscopy Techniques used are:
Combined with fluorophore labeled lectins with specificity for polysaccharide moieties, CLSM visualizes spatial distribution and abundance of EPS within biofilms. However, Scanning and Transmission Electron Microscopy (SEM, TEM) can be used to provide ultrastructural details of biofilm architecture, as well as, EPS matrix morphology. Atomic Force Microscopy (AFM) allows for mechanical properties such as stiffness and adhesion forces, to be measured at the nanoscale which can be linked to biofilm matrix integrity. Coupled with chromatographic separation or used for glycomic analysis, MS is used for structural elucidation of polysaccharide fragments and modifications [24, 25]. The emerging omics approaches (i.e. glycomics and metabolomics) combined with bioinformatics are aiding in the understanding of EPS biosynthesis regulation and biofilm dynamics.

Functional Roles of Polysaccharides in Biofilm Formation and Stability
Adhesion, Cohesion, and Scaffold Formation
The major scaffolding material for microbial biofilm extracellular polymeric substance (EPS) matrix is polysaccharide which contributes both to initial attachment to surfaces and to cohesive force keeping biofilm integrity. It is to provide the adhesive functions which means, microbial cells reversibly and later irreversibly attach to biotic and abiotic substrates via specific and nonspecific interactions via polysaccharide moieties. For instance, P. aeruginosa produces Psl, a mannose rich polysaccharide that confers strong surface adhesion during the stage of the biofilm development or the Pel that provides structural cohesion by means of its glucose rich matrix, maturing and increasing biofilm robustness [26, 27]. In addition, polysaccharide networks bring cells and other matrix components (including extracellular DNA and proteins) together to cross link and promote cell clustering into microcolonies and three dimensional biofilm architecture This scaffold confers mechanical stability against shear stress and environment perturbations by allowing biofilms to continue surviving in harsh niches and resist detachment [26, 28].

Protection Against Antibiotics, Immune Responses, and Environmental Stresses
These EPS matrix polysaccharides form a formidable barrier for penetration of antibiotics and shield against host immune defenses of biofilm embedded cells. Antihypertensives, however, are passed through a dense, hydrated polysaccharide matrix that limits diffusion rates of these agents and serves as a niche where microbial populations survive sub lethal concentrations and perpetuate the development of tolerant persister cells. As an example, the mucoid P. aeruginosa produced alginate acts as a barrier to this protective role by sequestering positively charged antibiotics like

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aminoglycosides and by impeding phagocytic clearance through a series of immune modulation [29, 30]. Hydration, integrity of biofilm structure, as well as protection against environmental stresses like desiccation and shear forces and oxidative stress are conferred by polysaccharides. Anionic polysaccharides such as alginate and some heteropolysaccharides, possess water retentive properties that overcome osmotic and drying challenges and possess viscoelastic properties that resist mechanical disruption [22, 31].

Regulation of Biofilm Physiology through Quorum Sensing and Intercellular Communication

The intricate links of polysaccharides with the regulation of biofilm physiology, its modulation of quorum sensing (QS) systems and intercellular signaling pathways are discussed in this review. QS which controls expression of genes important for EPS biosynthesis, biofilm maturation and dispersal, regulates these processes by the production and sensing of small diffusible signal molecules [32, 33]. The spatial localization and the concentration of polysaccharides within the EPS matrix will fine tune microbial community behavior by affecting the concentration gradients as well as the diffusion of QS signal signals. For instance, in P. aeruginosa, Psl and Pel polysaccharides prevent the establishment of the microenvironments that favor signalling in localized QS, a process which in turn governs the organization of the biofilm (its structural development, virulence factor production, etc. [29, 32]. In addition, polysaccharides are involved in physical interactions that mediate horizontal gene transfer and metabolic cooperation and are required for biofilm adaptation and survival in an ever shifting environment.

Biofilms formed by a polysaccharide are major pathogens have particular clinical significance

Many infectious diseases are associated with chronic and severe infection and further association with microbial biofilms rich in polysaccharides. In addition to providing stability of the biofilm architecture, the extracellular polysaccharide matrix confers a substantial boosting of microbial resistant against antimicrobial treatments and host immune defense. The clinical implications of polysaccharide mediated biofilms produced by major bacterial and fungal pathogens are discussed in this section regarding the modes of infection pathogenesis, the cause of chronicity and the nature of multidrug resistance [34].

P. aeruginosa: Alginate, Pel and psl in Lung and Deviceassocated Infections.

The ubiquitous opportunistic pathogen P. aeruginosa is infamous for the highly stable biofilms of polysaccharide-rich polymorphisms that it forms in impervious chronic lung infections (cystic fibrosis) and on indwelling medical devices. Three major exopolysaccharides (alginate, Pel and Psl) make up the majority of the biofilm matrix [35, 36]. An overproduced viscous, anionic polymer composed of β-D-mannuronic acid and α-L-guluronic acid known as alginate is overproduced by mucoid P. aeruginosa strains isolated from CF patients. Alginate protects bacteria from phagocytosis and penetration of antibiotics, modulates host immune responses and enables chronic

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infection survival, all of which contribute to lung tissue damage [36, 37].
Pel is a positively charged glucose rich polysaccharide which, through mediating tight cell cell interaction in the matrix, provides biofilm structural integrity and resistance to aminoglycosides. The surface attachment and biofilm formation is helped by psl which consists of mannose, glucose and rhamnose. It also increases the resistance for phagocytosis and the protection of immune evasion mechanisms [22, 38]. Polysaccharides produced in biofilms by P. aeruginosa synergistically promote recalcitrance of P. aeruginosa infections, in part and therefore contribute to poor treatment outcomes in P. aeruginosa associated infections of the ventilator, urinary tract and wound [37].

S. aureus and Staphylococcus epidermidis: Proteinaceous components in chronic infections of Staph infections

The formation of biofilms by Gram-positive pathogens S. aureus and S. epidermidis are the main cause of device related and chronic infections such as prosthetic joint infections, endocarditis and catheter related infections. These biofilms are enriched in a polysaccharide intercellular adhesin (PIA), more commonly referred to as poly-β-1,6-N acetylglucosamine (PNAG) which is the primary polysaccharide component. PNAG enables intercellular adhesion and supposes the accumulation stage of biofilm building as well as resistivity to host immune effectors and antibiotics [22, 39].
Not only are there PNAGs in S. aureus biofilms, but they also contain proteinaceous factors such as an accumulation Aap-associated protein, fibronectin-binding protein and extracellular matrix-binding proteins, all of which synergize with polysaccharides in contributing to the robustness of biofilms as well as the S. aureus potential for causing a chronic infection [39, 40]. Staphylococcus sp. biofilms, supported by the presence of PNAG, are notoriously persistent which is why they are resistant to the effects of conventional antimicrobial therapies and the immune system, resulting in inordinately high rates of therapy failure and relapse.

Roles of polysaccharides for multidrug resistance of K. pneumoniae and Acinetobacter baumannii

K. pneumoniae and A. baumannii are nosocomial pathogens that are highly prevalent multidrug resistant underlining and forming minimally characterized biofilms enriched with polysaccharides that increase their survival and virulence [41, 42]. The inner biofilm structure of K. pneumoniae biofilms is made of a polysaccharide capsule, largely contained of different capsular polysaccharides, known as K-antigens which are essential for immune evasion and stabilization of the matrix. Biofilm formation occurs at high rates and correlates with antibiotic resistance phenotypes: pneumonia, bloodstream infections or urinary tract infections, for example [43].
A. baumannii produces exopolysaccharides and capsular polysaccharides involved in biofilm formation on hospital surfaces and in the environment that are associated with increased resistance to desiccation, disinfectants and antibiotics. Horizontal gene transfer of resistance determinants in the biofilm lifestyle worsens resistance spread in clinical settings [44]. These polysaccharide rich biofilms are tough barriers that essentially defend bacteria from therapeutic intervention and so novel antibiofilm

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strategies are needed.

Targeting of Polysaccharide-rich Biofilms as a Therapeutic Strategy

Because of their resistance to conventional antimicrobial therapies, biofilms enriched in polysaccharides hold inherent resilience to antimicrobial therapies, resulting in the intense study of methods to disrupt or eradicate the extracellular polymeric substance (EPS) matrix. Attacking the polysaccharide portions of biofilms may be a means to disrupt integrity of the biofilm, increase penetration of antimicrobials and reverse the immunosuppression encompassed by biofilms. In this section, state of the art therapeutic approach such as enzymatic degradation, natural and synthetic antibiofilm agents, nanotechnology enabled delivery system, quorum sensing interference, immunotherapeutic intervention etc are discussed.

Enzymatic degradation of the Biofilm matrix

Enzymatic purging of biofilms includes the destruction of critical polysaccharides inside the EPS matrix, weakening the biofilm framework and advertising expulsion of microbes. Alginate lyases selectively loosen the alginate polymer in the P. aeruginosa biofilm thereby lowering the matrix viscosity and increasing antibiotic susceptibility. Studies shows that alginate lyase treatment in combination with aminoglycosides disrupts mature biofilms, especially for cystic fibrosis lung infection [45]. Dispersin B, a glycoside hydrolase, cleaves β1,6 -N-acetylglucosamine linkages in bacteria (S. aureus and E. coli) produced PNAG/PIA polysaccharides that disperses biofilms and enhances antibiotic efficiency [46]. Extracellular DNA (eDNA) is a major structural component in biofilms which is targeted for digestion by DNases. Polymicrobial communities are more effectively cleared and showed reduced infection severity in the setting of disruptors of the biofilm matrix induced by DNase treatment [47]. These enzymes are combined with conventional antimicrobials in which they exhibit enhanced disruption and eradication of biofilms.

Natural and Synthetic Antibiofilm Agents Targeting Polysaccharides

Natural agents pertained to plant — derived phenolics, flavonoids and polysaccharides such as chitosan which either disrupt EPS synthesis or trigger biofilm dispersal. Other potential therapeutic scaffolds are marine bacterial EPS with antiviral and antibiofilm activity [29, 48]. Synthetic molecules like glycosyltransferase inhibitors, inhibit the biosynthetic process of key exopolysaccharides and thus prevent biofilm formation. Given synthetic analogues that mimic natural antibiofilms agents, they have increased specificity and stability [49]. These phytochemicals, essential oils and quorum sensing inhibitors generally have two functions: modulating the growth of polysaccharide and disrupting biofilms already formed.

Anti-quorum sensing molecules and biofilm dispersal strategies

Disruption of the regulatory networks controlling polysaccharide synthesis, biofilm maturation and quorum sensing (QS) systems which are all targeted to affect biofilm maturation Small molecule QS inhibitors (QSI), like furanones, synthetic analogs and natural compounds interrupt signal generation or reception and in turn downregulate

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EPS biosynthesis genes and facilitate biofilm dispersion [50]. The presence of enzymes that degrade QS signals (e.g., lactonases) decreases pathogen robustness, biofilm and virulence factor expression [51]. Agents that cause biofilm dispersal, nitric oxide donors and cis-2-decenoic acid, affect intracellular signaling pathways such as cyclic di-GMP to further degrade the matrix and release the cells, thus rendering dispersed cells more susceptible to antibiotics [38, 52]. Conventional therapies against persistent biofilms are increasingly combined with incorporation of QS inhibition and dispersal inducing agents.

Conclusions and future prospective

The inherent heterogeneity of biofilms at genetic, phenotypic and microenvironmental levels makes biofilm associated infections formidable. Biofilms have a complex structure of polysaccharide rich subpopulations of cells with variable antibiotic susceptibilities resulting in the emergence of resistant persister cells. Dense polysaccharide matrices coupled with this heterogeneity make penetration of drug difficult and contribute to chronic infections. Furthermore, the polymicrobial nature of biofilms makes them even more difficult to treat, and hence, multi-targeted therapeutic strategies are required. Biofilm models that are unable to replicate in vivo complexity and difficulties in effective delivery of therapeutic agents are among the translational hurdles from laboratory research to clinical applications. The safety evaluations of new antibiofilm agents including enzymatic therapies and nanomaterials must be rigorous and biofilms may become resistant to these treatments. Omics, imaging and bioinformatics tools have recently been developed to improve our understanding of the biofilm composition and dynamics, opening the door for targeted therapeutic development. Because biofilms are heterogeneous and adaptive, personalized medicine approaches are necessary. Biofilm related infections are targeted by these approaches using molecular profiling, imaging and custom combination therapies. Microbiome editing, CRISPR based antimicrobials, and immune modulation may be used for the precise targeting of biofilm forming pathogens. Biofilm associated infections can only be effectively managed with an integrated multidisciplinary approach that encompasses microbiology, bioengineering, immunology and clinical medicine. Personalized medicine, use of novel bioactive compounds and vaccine development to address antimicrobial resistance and improve patient outcomes are the future directions.

Declarations

Author contribution: All authors contributing equally in this manuscript.
Conflict of interest: Authors declare no conflict of interest.

References

L. Karygianni et al., "Biofilm matrixome: extracellular components in structured microbial communities," Trends in microbiology, vol. 28, no. 8, p. 668-681, 2020.

B. S. Saharan, N. Beniwal, and J. S. Duhan, "From formulation to function: A detailed review of microbial biofilms and their polymer-based extracellular substances," The Microbe, p. 100194, 2024.

Online ISSN 3007-3197
Print ISSN 3007-3189

A. Zhao, J. Sun, and Y. Liu, "Understanding bacterial biofilms: From definition to treatment strategies," Frontiers in cellular and infection microbiology, vol. 13, p. 1137947, 2023.

A. Almatroudi, "Biofilm resilience: Molecular mechanisms driving antibiotic resistance in clinical contexts," Biology, vol. 14, no. 2, p. 165, 2025.

V. Ahuja et al., "Microbial exopolysaccharide composites in biomedicine and healthcare: trends and advances," Polymers, vol. 15, no. 7, p. 1801, 2023.

A. Schulze et al., "Biofilms by bacterial human pathogens: Clinical relevance-development, composition and regulation-therapeutical strategies," Microbial Cell, vol. 8, no. 2, p. 28, 2021.

E. G. Di Domenico, A. Oliva, and M. Guembe, "The current knowledge on the pathogenesis of tissue and medical device-related biofilm infections," Microorganisms, vol. 10, no. 7, p. 1259, 2022.

K. Sahoo, S. Meshram, and K. Sahoo Jr, "Biofilm Formation in Chronic Infections: A Comprehensive Review of Pathogenesis, Clinical Implications, and Novel Therapeutic Approaches," Cureus, vol. 16, no. 10, p. e70629, 2024.

H. Koo et al., "Targeting microbial biofilms: current and prospective therapeutic strategies," Nature Reviews Microbiology, vol. 15, no. 12, p. 740-755, 2017.

I. Liaqat et al., "Bioremediation of heavy metals polluted environment and decolourization of black liquor using microbial biofilms," Molecular Biology Reports, vol. 50, no. 5, p. 3985-3997, 2023.

Y. Hong, M. A. Liu, and P. R. Reeves, "Progress in our understanding of Wzx flippase for translocation of bacterial membrane lipid-linked oligosaccharide," Journal of Bacteriology, vol. 200, no. 1, p. e00154-17, 2018.

Y. A. Knirel and J. J. Kenyon, Biosynthesis of bacterial polysaccharides, in Polysaccharides of Microbial Origin: Biomedical Applications. 2021, Springer. p. 1-28.

S. D. Liston, E. Mann, and C. Whitfield, "Glycolipid substrates for ABC transporters required for the assembly of bacterial cell-envelope and cell-surface glycoconjugates," Biochimica et Biophysica Acta (BBA)-Molecular and Cell Biology of Lipids, vol. 1862, no. 11, p. 1394-1403, 2017.

C. Whitfield, S. S. Wear, and C. Sande, "Assembly of bacterial capsular polysaccharides and exopolysaccharides," Annual Review of Microbiology, vol. 74, no. 1, p. 521-543, 2020.

S. Das, "Genetic regulation, biosynthesis and applications of extracellular polysaccharides of the biofilm matrix of bacteria," Carbohydrate polymers, vol. 291, p. 119536, 2022.

S. Rana and L. S. B. Upadhyay, "Microbial exopolysaccharides: Synthesis pathways, types and their commercial applications," International journal of biological macromolecules, vol. 157, p. 577-583, 2020.

S. Akshaya and A. J. Nathanael, "A Review on Hydrophobically Associated Alginates: Approaches and Applications," ACS Omega, vol. 9, no. 4, p. 4246-4262, 2024.

J. Chung et al., "How three self-secreted biofilm exopolysaccharides of Pseudomonas aeruginosa, Psl, Pel, and alginate, can each be exploited for antibiotic adjuvant effects in cystic fibrosis lung infection," International Journal of Molecular

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Sciences, vol. 24, no. 10, p. 8709, 2023.
S. L. Cole and L. K. Jennings, The Biofilm Blueprint: Exopolysaccharide Form and Function in Bacterial Biofilms, in Biofilm Matrix. 2024, Springer. p. 1-42.
X. Lu et al., "Antibodies targeting a conserved surface polysaccharide are protective against a wide range of microbial pathogens producing β-1–6-linked poly-N-acetylglucosamine (PNAG)," Engineering, vol. 38, p. 69-76, 2024.
W. J. Nicolas et al., "Structure of the bacterial cellulose ribbon and its assembly-guiding cytoskeleton by electron cryotomography," Journal of Bacteriology, vol. 203, no. 3, p. e00371-20, 2021.
E. Balducci et al., "Polysaccharides' Structures and Functions in Biofilm Architecture of Antimicrobial-Resistant (AMR) Pathogens," International Journal of Molecular Sciences, vol. 24, no. 4, 2023.
A. N. Olaimat et al., "A Review of Bacterial Biofilm Components and Formation, Detection Methods, and Their Prevention and Control on Food Contact Surfaces," Microbiology Research, vol 15, no. 4, p. 1973-1992, 2024.
M. Relucenti et al. Microscopy Methods for Biofilm Imaging: Focus on SEM and VP-SEM Pros and Cons. Biology, 2021. 10, 51 DOI: 10.3390/biology10010051.
I. Liaqat et al., "Medicinal Plants Exhibited Promising Potential to Inhibit Biofilm Formation by Catheter-Associated Bacteria in UTI Patients from Lahore, Pakistan," Journal of Oleo Science, vol. 74, no. 2, p. 221-232, 2025.
M. A. Rather, K. Gupta, and M. Mandal, "Microbial biofilm: formation, architecture, antibiotic resistance, and control strategies," Brazilian Journal of Microbiology, vol. 52, no. 4, p. 1701-1718, 2021.
P. Di Martino, "Extracellular polymeric substances, a key element in understanding biofilm phenotype," AIMS Microbiology, vol. 4, no. 2, p. 274-288, 2018.
H. Agarwal et al., "Capturing the micro-communities: Insights into biogenesis and architecture of bacterial biofilms," BBA Advances, vol. 7, p. 100133, 2025.
S. Singh et al., "Bacterial exo-polysaccharides in biofilms: role in antimicrobial resistance and treatments," Journal of Genetic Engineering and Biotechnology, vol. 19, no. 1, p. 140, 2021.
N. Muhammad et al., "Indigenous aseel chicken-derived probiotics as biofactories of antifungal metabolites to control mycotoxin contamination in poultry feed," Molecular Biology Reports, vol. 52, no. 1, p. 724, 2025.
N. Kaur and P. Dey, "Bacterial exopolysaccharides as emerging bioactive macromolecules: from fundamentals to applications," Research in Microbiology, vol. 174, no. 4, p. 104024, 2023.
J. N. Carey et al., "Quorum sensing regulation of Psl polysaccharide production by Pseudomonas aeruginosa," Journal of Bacteriology, vol. 206, no. 12, p. e0031224, 2024.
J. Lin and J. Cheng, Quorum Sensing in Pseudomonas aeruginosa and Its Relationship to Biofilm Development, in Introduction to Biofilm Engineering. 2019, American Chemical Society. p. 1-16.
L. Farah et al., "Development of Microbial Biofilms and Their Role in device, non-device and organ system level Infections," BioScientific Review, vol. 7, no. 2, p. 32-53, 2025.

Online ISSN 3007-3197
Print ISSN 3007-3189

M. T. Thi, D. Wibowo, and B. H. A. Rehm, "Pseudomonas aeruginosa Biofilms," International Journal of Molecular Sciences, vol. 21, no. 22, p. 8671, 2020.
F. F. Tuon et al., "Pathogenesis of the Pseudomonas aeruginosa Biofilm: A Review," Pathogens, vol. 11, no. 3, p. 300, 2022.
M. d. M. Cendra and E. Torrents, "Pseudomonas aeruginosa biofilms and their partners in crime," Biotechnology Advances, vol. 49, p. 107734, 2021.
X. Wang et al., "Biofilm formation: mechanistic insights and therapeutic targets," Molecular Medicine, vol. 4, no. 1, p. 49, 2023.
C. R. Arciola et al., "Polysaccharide intercellular adhesin in biofilm: structural and regulatory aspects," Frontiers in Cellular and Infection Microbiology, vol. 5, p. 7, 2015.
Q. Peng et al. A Review of Biofilm Formation of Staphylococcus aureus and Its Regulation Mechanism. Antibiotics, 12, 12, 2023.
N. V. Kolupaeva et al., "Acinetobacter baumannii and Klebsiella pneumoniae Isolates Obtained from Intensive Care Unit Patients in 2024: General Characterization, Prophages, Depolymerases and Esterases of Phage Origin," Viruses, vol. 17, no. 5, p. 623, 2025.
H. Mukhopadhyay et al., "Multidrug resistant Acinetobacter baumannii: A study on its pathogenesis and therapeutics," Current Research in Microbial Sciences, vol. 8, no. p. 100331, 2025.
L. Xu et al., "Klebsiella pneumoniae capsular polysaccharide: Mechanism in regulation of synthesis, virulence, and pathogenicity," Virulence, vol. 15, no. 1, p. 2439509, 2024.
A. Gedefie et al., "Acinetobacter baumannii Biofilm Formation and Its Role in Disease Pathogenesis: A Review," Infection and Drug Resistance, vol. 14, p. 3711-3719, 2021.
M. Charęza et al., "Enhancement of Inhibition of the Pseudomonas sp. Biofilm Formation on Bacterial Cellulose-Based Wound Dressing by the Combined Action of Alginate Lyase and Gentamicin," International Journal of Molecular Sciences, vol. 24, no. 5, 2023.
O. Sedighi et al., "Nanoparticle-Based Strategies for Managing Biofilm Infections in Wounds: A Comprehensive Review," ACS Omega, vol. 9, no. 26, p. 27853-27871, 2024.
D. Campoccia, L. Montanaro, and C. R. Arciola, "Extracellular DNA (eDNA). A Major Ubiquitous Element of the Bacterial Biofilm Architecture," International Journal of Molecular Sciences, vol. 22, no. 16, 2021.
A. K. Abdalla et al., "Exopolysaccharides as Antimicrobial Agents: Mechanism and Spectrum of Activity," Frontiers in Microbiology, vol. 12, p. 664395, 2021.
E. Razvi et al., "Small Molecule Inhibition of an Exopolysaccharide Modification Enzyme is a Viable Strategy To Block Pseudomonas aeruginosa Pel Biofilm Formation," Microbiology Spectrum, vol. 11, no. 3, p. e0029623, 2023.
H. F. Hetta et al., "Quorum Sensing Inhibitors: An Alternative Strategy to Win the Battle against Multidrug-Resistant (MDR) Bacteria," Molecules, vol. 29, no. 15, 2024.
R. Sikdar and M. Elias, "Quorum quenching enzymes and their effects on virulence,

Online ISSN 3007-3197
Print ISSN 3007-3189

biofilm, and microbiomes: a review of recent advances," Expert Review of Anti-infective Therapy, vol. 18, no. 12, p. 1221-1233, 2020.

J. B. Kaplan, "Biofilm Dispersal: Mechanisms, Clinical Implications, and Potential Therapeutic Uses," Journal of Dental Research, vol. 89, no. 3, p. 205-218, 2010.