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Microbial Biofilms: Understanding Their Formation and Impact

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ABSTRACT

Biofilms are structured communities of microorganisms embedded in a self-produced extracellular matrix, which can form on both living and inert surfaces. These biofilms provide protection to microbes against various environmental stresses, such as extreme pH, temperature, antibiotics, and radiation. The matrix, primarily composed of exopolysaccharides, facilitates microbial adhesion and promotes communication between cells. While biofilms are essential for microbial survival, they can pose significant challenges in industries like food processing, where they contribute to contamination by harmful pathogens. Biofilms can be formed by a wide range of microorganisms, including bacteria like *Pseudomonas aeruginosa* and *Staphylococcus aureus*. Despite their negative implications, biofilms also have beneficial roles in natural processes and applications such as wastewater treatment. Understanding their formation, structure, and control is crucial for managing their impact in both beneficial and harmful contexts.

INTRODUCTION

In order to protect microorganisms against a variety of adverse environmental circumstances, such as electromagnetic radiation, unsafe pH levels, temperature extremes, too much salinity, increased stress, malnutrition, and antibiotic exposure, biofilms are essential. Biofilms, which act as a kind of "protective clothing" for bacteria, help microbial communities become more resistant by establishing optimal conditions and encouraging the sharing of materials and information between microorganisms. These self-defence mechanisms in microbial development differ from the biological characteristics, environmental sensitivity, and morphological structure of plankton. Microbes use the complex three-dimensional structure of biofilms as a natural barrier and protective coating. Furthermore, it has been widely proven by substantial study that biofilms are a major cause of pollution in situations relevant to food (Flemming *et al*., 2016). One crucial and enduring element causing contamination in the food business is the continuous presence of biofilms on surfaces and equipment used in food contact. Another way to describe biofilms is as a grouping of one or more types of bacteria that may develop on different surfaces. They consist of microorganisms like protists, fungus, and bacteria. The complex communities of microorganisms that are attached to a surface or that most likely aggregate without attaching to a surface are known as biofilms. A biofilm is a collection of microorganisms that are affixed to the surface of a substrate and immersed in an extracellular slimy matrix. Communities of bacteria known as microbial biofilms form on surfaces and create an extracellular matrix that protects them. Enterococcus faecalis, Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus viridans, E. coli, and Pseudomonas aeruginosa are the most frequent bacteria that can produce biofilms, while both gram positive and gram-negative bacteria can do so. Examples of these include Pseudomonas aeruginosa, Staphylococcus aureus, and a few other bacteria (Haaber *et al*., 2012), and they are safely concealed in an extracellular matrix (ECM). They can have both beneficial and harmful impacts and can be found in a wide range of natural and man-made situations. The article offers information on the makeup of microbial biofilms and the composition, application and control practices of biofilms.

Composition of biofilms

90% water and 10% microbiological stuff make up a biofilm. Polysaccharides create a matrix within the biofilm and comprise between 50 and 90 percent of the organic component (Table 1). The intertwining of these polysaccharide strands results in a thick, mesh-like structure. Mechanical strength is increased by the hydroxyl groups in the polysaccharides through intermolecular interactions. Positively charged ions like Ca^{2+} or Mg^{2+} can be incorporated into biofilm architecture to form cross-bridges that support polymers and enable biofilms to thicken to 300 µm (Alsuwat *et al*., 2025). Alternatively, polysaccharides in biofilms can be impartial or polyanionic, as shown in the extracellular polymeric substances (EPS) of Gram-negative bacteria. The presence of uronic acids, such as ketal-linked pyruvates, D-glucuronic, and mannuronic acids, can also confer anionic properties on biofilms. The binding force of mature biofilms and interlacing polymer strands is strengthened by their anionic properties, which encourage the interaction of divalent cations. For Gram-positive bacteria like Staphylococci, the chemical composition of EPS is distinctly cationic. The slime of coagulase-negative microorganisms is made up of trace amounts of proteins and teichoic acid. The structural stability of EPS is supported by the various charges and ions in the biofilm, which allows biofilms to withstand hazardous trimming force situations like impact sites on waterfalls. Sessile bacteria that thrive in biofilms are essential to the biofilm environment's optimal physiological function. Sessile microbial biofilm groups exhibit varying growth patterns, transcription and translation rates, and gene expression rates. These advantageous characteristics develop as sessile microbial biofilm groups adapt to microenvironments with higher osmolality, less resources, and thicker cells.

Table 1. Composition of biofilms

Components	% of matrix
Water	Up to 90%
Microbial cells	2-5%
Polysaccharide (Homo & Hetero)	1-2%
Proteins	< 1-2 %, including enzyme
DNA & RNA	< 1-2 % From lysed cells

Structure and biofilm formation

The formation of a biofilm is actually the result of a number of biological, chemical, and physical processes that take place over time. Figure 1 provides detailed instructions on how bacterial biofilms are formed.

1. ***Initial attachment of bacterial cells: -*** Microorganisms initially attach to a surface through weak, reversible interactions such as Van der Waals forces and electrostatic interactions.

2. ***Cell aggregation and accumulation in multiple cell layers (Micro colony formation): -*** Attached microorganisms produce extracellular polymeric substances (EPS), which help to anchor the microorganisms to the surface and promote the aggregation of cells into micro colonies.

3. ***Biofilm maturation: -*** As the micro colonies grow, they become more complex and develop into a mature biofilm. The EPS matrix becomes more organized and forms a three- dimensional structure that can include channels and voids.

4. ***Dispersal (detachment):*** At some point, biofilms may disperse or release individual cells or clusters of cells into the surrounding environment to colonize new surfaces or environments.

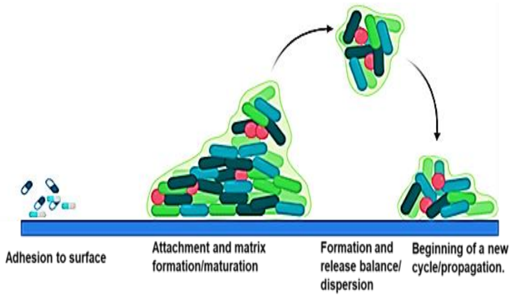

Figure 1. Biofilm formation process/steps (Source: Created in bioRender.com)

Applications of biofilms

Biofilms have diverse applications across various industries and fields due to their unique characteristics and functionalities. Some of the notable applications of biofilms include:

- ✓ ***Bioremediation:*** Biofilms can be used to clean up contaminated environments by degrading pollutants and toxins. They are particularly effective in treating wastewater and remediating oil spills.

- ✓ ***Wastewater treatment:*** Biofilms play a crucial role in biological wastewater treatment processes, such as activated sludge systems and trickling filters. They help break down organic matter and remove nutrients like nitrogen and phosphorus from wastewater.

- ✓ ***Biocorrosion control:*** In industrial settings where metal surfaces are exposed to microbial corrosion, biofilms can be engineered to form a protective layer, preventing further damage.

- ✓ ***Medical devices:*** Biofilms are often involved in medical device-related infections. Understanding their behaviour helps in developing strategies to prevent or treat device-associated infections.
- ✓ ***Biotechnology:*** Biofilms are utilized in biotechnological processes for the production of enzymes, biofuels, and other valuable bio-based products.
- ✓ ***Agriculture:*** Biofilms can aid in the development of beneficial microbial communities in the soil, enhancing nutrient availability and promoting plant growth.
- ✓ ***Food industry:*** Biofilms can form on food processing surfaces, leading to contamination and reduced food safety. Understanding and controlling biofilm formation is crucial in ensuring food hygiene.
- ✓ ***Dental plaque:*** Dental plaque is a biofilm that forms on teeth, leading to dental caries and gum disease. Understanding biofilm dynamics helps develop better oral hygiene practices.
- ✓ ***Antifouling coatings:*** In marine environments, biofilms can attach to submerged surfaces, leading to fouling. Antifouling coatings are designed to prevent or reduce the adhesion of biofilms to these surfaces.
- ✓ ***Biomedical applications:*** Biofilms are investigated for potential use in tissue engineering, where they can serve as scaffolds for growing new tissues or promoting wound healing.
- ✓ ***Biofilm sensors:*** Biofilms can be utilized as biosensors to detect specific substances or changes in their environment. This application has potential applications in environmental monitoring and healthcare.
- ✓ ***Environmental monitoring:*** Biofilms can act as indicators of water quality in natural environments, providing insights into ecosystem health.
- ✓ ***Microbial fuel cells:*** Biofilms can be used in microbial fuel cells to convert organic matter into electricity.
- ✓ ***Biofilm-based technologies:*** Advances in understanding biofilm biology have led to the development of biofilm-based technologies for various applications, from biodegradable plastics to bio surfactants production.

Advantages of Biofilms: -

- ✓ Biofilms provide protection against environmental stressors, such as antibiotics and disinfectants.
- ✓ Microorganisms in biofilms have access to nutrients and space for growth and replication.
- ✓ Biofilms can facilitate microbial interactions, such as cooperation and competition.
- ✓ Biofilms contribute to biogeochemical cycles, such as the cycling of carbon, nitrogen, and sulphur.
- ✓ Biofilms can have positive effects on human health, such as beneficial oral biofilms that prevent dental caries.
- ✓ Biofilms can be used in biotechnological applications, such as wastewater treatment and bioremediation.

Disadvantages of Biofilms: -

- ✓ Biofilms can cause infections in humans, animals, and plants.

- ✓ Biofilms can form on industrial surfaces and cause corrosion and fouling.
- ✓ Biofilms can cause clogging of pipes and filters in water treatment systems.
- ✓ Biofilms can lead to food spoilage and contamination.
- ✓ Biofilms can harbour pathogenic microorganisms that are resistant to antibiotics and disinfectants.
- ✓ The formation of dental caries, medical device infections

Control of Biofilms: -

- ✓ Physical methods, such as mechanical removal and ultrasonic treatment, can disrupt biofilms.
- ✓ Chemical methods, such as antimicrobial agents and disinfectants, can kill or inhibit biofilm formation.
- ✓ Biological methods, such as bacteriophages and probiotics, can target specific microorganisms in biofilms.

CONCLUSION:

Microbial injury and biofilms are complex and multifaceted phenomena with both positive and negative impacts. Effective control and management of biofilms are crucial in various industries to ensure food safety, prevent infections, and maintain the overall health of ecosystems. Advances in biofilm research and their applications continue to hold promise for sustainable solutions and improved human well-being.

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