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A Brief Review on the Crucial Significance of Anti-Biofouling Surfaces in Medical and Engineering Applications

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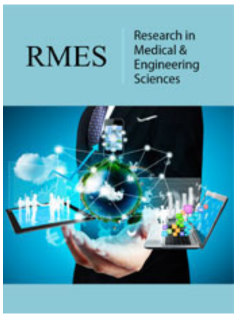

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Abstract

Based on the nature of accumulated foulants, fouling is classified into organic, inorganic, particulate, and biological categories. Among these categories, the last one, i.e., biofouling, is considered the most problematic, posing numerous challenges in industry, medicine, and other fields. Biofouling is the accumulation of micro and/or macro biological compounds such as proteins, peptides, cells and cellular components, bacteria, COVID-19 virus, yeast, fungi and algae on surfaces. Given the critical importance of identifying and predicting biofouling, establishing efficient control, and adopting suitable strategies to minimize associated damage becomes essential. This review focuses precisely on addressing this crucial issue.

Keywords: Anti-biofouling surface; Biofouling; Biological compounds; Foulants; Polyethylene glycol; Zwitterionic polymers

Introduction

Biofouling generally refers to the nonspecific adsorption of proteins, peptides, amino acids, nucleic acids (like DNA and RNA), cells or microorganisms on the surfaces of substrates. This undesired event is a significant and inclusive challenge for a wide range of applications, comprising but not limited to medical devices, targeted drug delivery systems, chemical sensors, marine and industrial equipment, food packaging and storage and separation membrane systems. For instance, the uncontrolled adhesion of biological compounds on the surface of implanted biomaterials in contact with physiological fluids and tissues can have adverse effects on the wound healing process and pose serious risks to human health. In another example, the adsorption of proteins reduces the sensitivity in the case of in vitro diagnostics, such as immunological assays and sensors. As the last example, membrane biofouling is inevitable in membrane-based separations dealing with different solutions being treated, leading to detrimental effects on membrane performance and separation efficiency [1-7].

The design and construction of anti-biofouling surfaces with the ability to minimize the undesired occurrence of nonspecific adsorption of biological materials is a substantial and outstanding challenge. The first crucial consideration is long-term stability during long-term use. The antifouling functions should not be easily compromised by detachment or scratching caused by physical damage or chemical degradation from exposure to oxygen, water, or possible catalytic ions in media [1,6,8].

Several strategies have been proposed in the literature for the construction of these surfaces commonly referred to as anti-biofouling surfaces. Despite their diversity, these strategies follow two major principles: (1) preventing biofoulants from attaching to the surface and (2) degrading or killing them using biocides [1, 2].

A common way to avoid the problems arising from biological uptake on the surface is to coat it with a layer of material that inhibits nonspecific interactions. There are various types of hydrophilic polymers and non-polymer materials that exhibit anti-biofouling properties [2,9,10].

Polyethylene glycol (PEG) and its derivatives are the most commonly employed polymers to impart anti-biofouling ability to a surface. This interest results from the fact that PEG is non-toxic, non-antigenic, non-immunogenic as well as highly hydrophilic, and biocompatible [11]. The structure of PEG is generally expressed as $H\text{-}(O\text{-}CH_2\text{-}CH_2)n\text{-}OH$. The protein adhesion resistance of PEG-functionalized surfaces can be interpreted in such a way that as proteins approach the surface, the PEG chains are compressed, producing a repulsive elastic force that causes the proteins to move away from the surface. In addition to the steric hindrance effect, hydration is another reason for the protein resistance of PEG-modified surfaces. Each ethylene glycol unit in the PEG chain can strongly bind to water molecules via hydrogen bonding, resulting in the formation of a hydrated barrier against biomolecules absorption [11,12]. The surface packing density and chain length of the grafted PEG are two parameters influencing the magnitude of protein repulsion from the surface [12].

Although PEG-based materials are the first choice for imparting protein resistance to a surface, they tend to be auto-oxidized and degraded in the presence of oxygen; hence, their antifouling capabilities for long-term applications are limited [13].

Zwitterionic polymers are efficient alternatives to PEG thanks to their super hydrophilic and antifouling properties resulting from the presence of abundant ions and subsequent strong hydration layer. These polymers are characterized by an equal number of cationic and anionic groups in their macromolecular chains, leading to an overall charge neutrality. This unique molecular structure and property features make them promising candidates to combat long-term biofouling problems. They exhibit the ability to resist nonspecific protein adhesion, bacterial adsorption, and biofilm formation [8,14-16]. Zwitterionic polymers can be divided into polybetaines and polyampholytes. The difference between the two polymers lies in the fact that the first category contains a positive and negative charge on the same monomer unit, whereas the second category is formed by a pair of separate monomers with two oppositely charged moieties mixed in a 1:1 ratio prior to co-polymerization [16,17].

PEG-based and zwitterionic coatings are examples in which the induction of anti-biofouling property is mainly through the first strategy, i.e., preventing biofoulants from attaching to the surface. However, these coatings, which repel biological compounds and prevent their attachment to the surface, may also exhibit some resistance to the attachment of microorganisms, such as bacteria. Therefore, it is extremely desirable to design coatings that are bactericidal to prevent the risk of bacterial infection. In this case, by using the second strategy and the incorporation of biocidal agents (like antibiotics, silver, enzymes, peptides, polycations and photoactive agents) on the surface, antibacterial property is induced [1,2].

Conclusion

In conclusion, it is important to acknowledge the remarkable progress that has been made in the design and construction of anti-biofouling surfaces. However, there is much optimism for the development of even more advanced solutions in the future, drawing upon both strategies mentioned in the text.

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