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REVIEW ARTICLE

A Selective Review on the Novel Approaches and Potential Control Agents of Anti-biofouling and Anti-biofilming

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Abstract
Specific aggregates of bacterial colonies, which, when embedded in a self-produced matrix, are known to cause biofouling. These complex structures are highly resistant to extreme stress conditions like antibiotics, complex cleaning strategies, or even the human immune system. The formation of biofilm matrices and biofouling is chosen as the preferred microbial environment owing to the advantages offered for the embedded cells for their long-term survival. This increased resistance and virulence emphasizes the urgency of finding newer alternatives for its complete eradication. Combined approaches using enzymes, biomimetic surface modification, and a fusion of physical and chemical methods are gaining more prominence. In brief, this review discusses the structure and biology of biofilms, their mechanism of action, and the new-age anti-biofilm and biofouling agents in food industries, bioelectric, and medical devices. Current anti-biofouling methods, including engineered polymers, surface coatings to antimicrobials, and antibiotics, have also been described.

Keywords Biofilm · Extracellular polymeric matrix · Anti-biofouling · Anti-biofilming · Resistance

Introduction

Biofouling is the undesirable formation of microbial layers on top of surfaces. This accumulation and attachment of unwanted biological matter on inert or living surfaces with the help of microorganisms and macro-organisms leads to the formation of biofilms. It can occur by coming at any solid–liquid, liquid–air, or solid-air contact, and almost 99% of the microorganism can form biofilms [1]. One of the powerful strategies of microorganisms' survival is biofilm formation. Almost all biofilms' composition is essentially the same. The matrix has a large portion filled with water, and the

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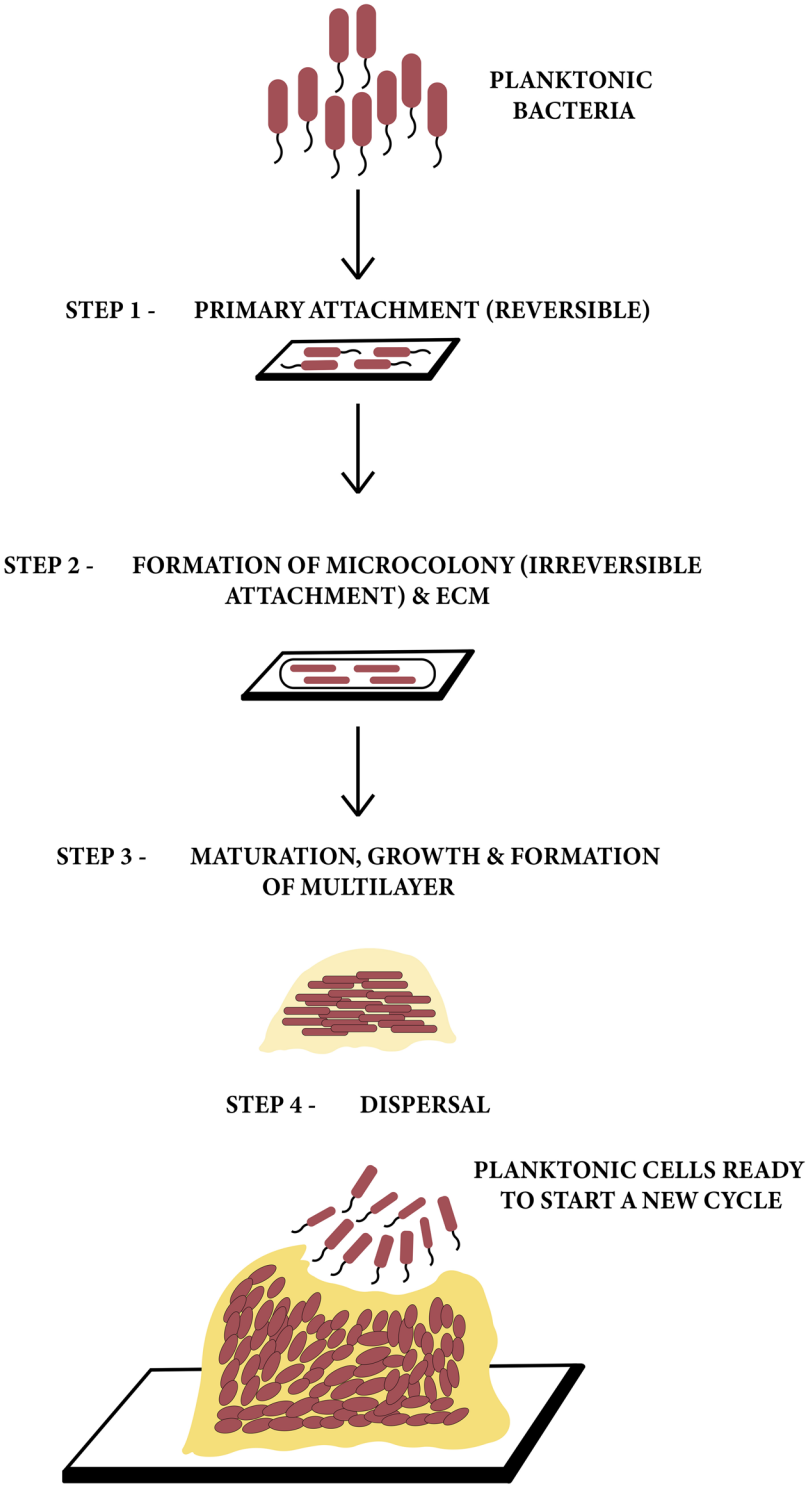
Fig. 1 The whole process of biofilm formation ▶

residue consists of extracellular polymeric substances (EPS), which constitutes around 50–95% of the biofilm structure. The EPS consists of proteins and polysaccharides. Due to the presence of EPS, bacteria in the biofilm become more resistant to any antimicrobial treatment. It helps maintain a steady and constant arrangement of synergistic micro-consortia consisting of different species. One of the first living organisms to exist on earth was fossilized biofilms that dated back to approximately 3.5 billion years. Thus, it is one of the most successful life forms found anywhere [2].

Biofouling was described as the deposition of undesired material on surfaces and microorganisms' attachment to develop biofilm further. Moreover, it was said that neither metal nor plastic could resist bacterial colonization. From living tissues like organ implants (cystic fibrotic lung), catheters, human tooth, to non-living surfaces like industrial or hospital equipment, natural aquatic, or semi-aquatic surfaces, biofilm can form anywhere. It also provides other definitions, i.e., (a) organic fouling is the accumulation of organic substances like oil, humid substances, and proteins, (b) scaling and mineral fouling or crystalline fouling is the accumulation of inorganic compounds which precipitate on a surface, and (c) particulate fouling—the accumulation of clay, silica, debris, and solid particles suspended in aqueous substances like water or any other fluids. Even if 99.99% of all the contaminating microorganisms are eliminated, a few still manage to enter the system and contaminate it [3]. All plants that manufacture wet products are susceptible to host biofilms. In between two disinfection or cleaning processes, microorganisms have time to start a process of colonization. This biofilm formation can begin within less than 2 h. However, it might be less exhibiting than those formed throughout several months [2, 3].

Structure and Mechanism of Biofilm Formation

Many species of bacteria can switch between planktonic and biofilm stages. The planktonic bacteria have a high reproduction rate. Moreover, cells in the biofilm stage are 1000 times more robust and resistant than their planktonic stages. There are several reasons why bacteria initiate biofilm formation, i.e., it increases the stress tolerance of the bacterial cells and resists the harsh external environment. Due to its strong shear forces, it becomes resistant to being washed away by water or the flow of water or bloodstream by getting attached to a surface. Also, the biofilm layers consisting of EPS protect the bacteria from various antimicrobial agents. Biofilms restrict the mobility of the bacteria and increase the cell density, which acts as a favourable environment for eDNA (extracellular DNA, viz. plasmid) exchange with the help of conjugation, some of which also assist in antibiotic resistance. Moreover, the horizontal gene transfer rate is higher in the biofilms than in the planktonic cells. The initial requirement for the process of biofilm formation to begin is that the microorganism should not be too away from the surface [4]. Figure 1 describes the whole process of biofilm formation. It involves four steps which includes the planktonic bacteria attaching itself on the surface and formation of a matrix. This is followed by the maturation, growth, and a multilayer formation. It eventually disperses and allows the planktonic cells to start a new cycle.


PLANKTONIC BACTERIA
STEP 1 - PRIMARY ATTACHMENT (REVERSIBLE)
STEP 2 - FORMATION OF MICROCOLONY (IRREVERSIBLE ATTACHMENT) & ECM
STEP 3 - MATURATION, GROWTH & FORMATION OF MULTILAYER
STEP 4 - DISPERSAL
PLANKTONIC CELLS READY TO START A NEW CYCLE

Physical Surface Interactions and Signalling in Biofilms

When bacteria is about 10–20 nm away from the surface, the negative charges are repelled by environmental factors. This repulsion is overcome by van der Waals forces present between the bacterial cells, flagella, curli filers, and other membrane proteins that provides mechanical support to the surface. Other non-specific interactions include hydration, hydrophobic, and steric forces which influence the cell attachment. The best-studied phenomena among them include hydrophobic and electrostatic ones. Elasticity, topography, stiffness, and mechanical stability help in the regulation of the physiology of bacteria, their adhesion, and growth into biofilms. Upon response, the bacterial cells secrete DNA, lipids, proteins, and lipopolysaccharides, which accumulate and eventually form the EPS [5]. Microorganisms like *Vibrio parahaemolyticus* have been noted to increase their flagellar count upon surface attachment, which initially had a single polar flagellum prior to its adhesion. This surface motility is referred to as swarming.

Further surface sensing mechanisms have been found in *P. aeruginosa*, involving the Wsp system. As soon as the bacterium responds to a surface, the c-di-GMP cyclase or synthase is produced. However, the nature of the signal is still a mystery. Another mechanism followed is the Pil-Chp system which involves a cascade of intracellular signalling molecules. An MCP-like protein PilJ signals the protein CyaB to stimulate its activity upon surface adhesion. The planktonic cells previously did not encounter low cAMP levels and are referred to as surface naive. These cells initially undergo transient interactions and thus reversible attachment. The cAMP levels build up after attachment and detachment of the cells due to the Oil-Cap surface sensing mechanism. As soon as the cAMP levels become high and progress into irreversible stages of attachment, it is referred to as surface sentient planktonic bacterium. These surface sentient bacterium then remain adhered and eventually develop into biofilms [6].

Quorum Sensing (QS)

Bacterial species are highly reactive; upon inhibiting biofilms, they communicate and respond to the local cell density through a process called quorum sensing. For example, in Gram-negative species like *P. aeruginosa*, quorum sensing systems are las and rhl. Each system has its own AHL (acyl-homoserine-lactone) synthase and transcriptional regulator. These systems are essential for releasing extracellular DNA in the PAO1 strain, which helps biofilm formation.

In Gram-positive organisms, the quorum-sensing molecules are often peptides. They are detected outside the cellular environment, which is sensed by kinases that help to activate cognate response regulators through phosphorylation, which further triggers the target gene expression. For *S. aureus*, the autoinducer molecule is a peptide obtained from the agrD gene. The tangled steps in biofilm formation are almost the same and involve initial attachment, cell-to-cell adhesion, maturation, and the final detachment. The bonding is favoured when agr quorum sensing is inhibited. Upon cell attachment, bacteria start forming biofilms by triggering the production of the exopolysaccharides known as PNAG or PIA. The mutants which lack the agr gene start forming thick biofilms than those of the wild type owing to the inability of the cells to detach from the mature biofilms.

Other signalling molecules that do not engage in quorum sensing include secondary metabolites like antibiotics, pigments, and siderophores. Scientists noted that subinhibitory

concentrations of antibiotics like imipenem and tobramycin induced thicker biofilms in *P. aeruginosa* and *E. coli.* Moreover, *P. aeruginosa* also responds to small molecules like phenazines which are redox-active pigments and possess antibiotic activity or virulence agents in eukaryotic hosts. Inside the biofilm environment, phenazine helps in extracellular electron transfer to generate energy in growth [7].

Mechanism of Biofilm Formation

The three steps which occur in biofilm formation are attachment, maturation, and dispersion. Attachment can be divided into reversible and irreversible processes. Cells that have been newly adhered are loosely attached and associated with the surface and are ready to detach. With time, the individual cells enter an irreversible stage of attachment where the bacterial cells lie flat against the wing's surface and resist its attempt of physically dislodging them. Then, the cells multiply, initiate biofilm matrix production, and eventually form the small aggregates of bacteria called the microcolonies [6]. The irreversibly attached biofilm can tolerate supplementary physical and chemical shear forces. Flagella, type IV pili help in the motility, initial interaction across the surface, and connecting the cells in aggregation and forming microcolonies. The quorum sensing mainly occurs in the microcolony formation stage, where it secretes signalling molecules and regulates gene expression, thus promoting EPS formation.

Finally, after attaching microcolonies onto surfaces, the biofilm maturation takes place where it withstands shedding. The attachment depends on the biofilm components, gene regulation, and quorum sensing, which is significant for its development. A mature biofilm has three features: the outer layer where the plankton survives, the middle layer composed of a compact microbial basement, and the inner layer formed of a regulating film. Post maturation, the outer layer is free to float to other areas. The detachment is considered the foremost step behind the spread of pathogens; thus, biofilm development and separation mechanism are crucial components for understanding its inhibition and preventing infection [8].

Components of a Mature Biofilm

Table 1 describes the composition of a typical biofilm. Exopolysaccharides are familiar structures of bacterial biofilms: the extracellular matrix. Post attachment, the cells begin the production and the accumulation of the extracellular polymers, which surround each other eventually and develop the microcolony. The process can occur within a few hours after the primary adhesion. The polysaccharides (a primary component of biofilm) are hydrophilic, although some could be hydrophobic. They contain non-carbohydrate substituents mainly specific to species and have a negative charge. This kind of matrix promotes the entry and accession of ions and molecules [9]. Despite all, how the bacteria sense a surface for attachment is a crucial question. Post adhesion, the microorganisms produce EPS, multiply within the formed matrix, and ultimately produce a biofilm. The formation time varies from hours to days and sometimes months to reach a state of equilibrium, depending on the culture conditions [2].

Another substantial component of the EPS matrix is the extracellular proteins attached to the surfaces of cells and the polysaccharides, which help in the formation of biofilm and its stabilization. However, many enzymes are also involved in biofilms' internal degradation, which helps in the breakdown of biopolymers and provides energy and carbon

Table 1 Exopolysaccharides and respective microorganisms

Name of the microorganism	Exopolysaccharides secreted	References
Bacillus subtilis	EPS poly-δ-glutamate	[10]
A. baumannii, *E. faecalis*, *K. pneumoniae*, *P. aeruginosa*, *Enterococcus*. spp	Most abundant: mannose, galactose, and glucose; followed by arabinose, fucose, N-acetyl-glucosamine, galacturonic acid	[7]
P. aeruginosa	Pel, Psl, and alginate (Alginate also protects the cells from antibiotics like ceftazidime, ciprofloxacin, gentamicin, and ticarcillin.)	[11]
Staphylococcus spp.	Polysaccharide intercellular adhesin (PIA)	[12]
S. aureus	N-acetyl glucosamine (PNAG) or polysaccharide intercellular adhesin (PIA)	[7]

resources to the cells during starvation. The degradation of the matrix with enzymes help release biofilm cells and assist in a new lifecycle so that the bacterial colonization continues. Some of the adhesive proteins secreted by various microorganisms are discussed in Table 2. Yet another component of the biofilm matrix is the extracellular DNAs (eDNAs). The negative charge of the eDNA acts as a repulsive force for the initial attachment. eDNA starts to interact with the receptors present on the surface of the substratum for initiating adhesion. It depends on the minimum distance between cells and the surface. *P. aeruginosa*, *S. aureus*, contains notable amounts of eDNA, which helps provide cell movement and stability to the biofilm layers. In *S. epidermidis*, eDNA inhibited the vancomycin transportation within the biofilms, protecting bacteria embedded inside the biofilm surface [6].

Current Exploitation of Antifouling and Anti-biofilming

The severity of biofouling and biofilm formation depends on various parameters like salinity, temperature, light, geography, depth, and surrounding factors. The existence of bacterial colonies inside a biofilm represents an essential survival strategy. It also offers resistance to many antimicrobials. The current review article will significantly emphasize the prevention and proper mitigation of biofilms in industries like food and medicine.

Food Industry

Any bacteria present in food equipment poses the risk of causing food poisoning, endangering human health, disrupting food hygiene, and immense economic loss. Since biofilms protect the bacteria and increase its resistance from clinical antibiotics, disinfectants, and fungicides, it is a severe threat to human health. Accordingly, adequate measures must be implemented against biofouling and biofilm formation. Some of them are discussed here.

Cleaning and Disinfection

Complete elimination of biofilm is a challenging task. It can cause energy losses and blockages in industrial equipment like condenser tubes, heat exchangers, and water circuits, which is highly unhygienic and fatal for human consumption. Both mechanical and chemically cleaning eliminate fouling. Besides cleaning, disinfection also destroys any residual microorganisms and is one of the most critical steps for reducing microbial colonization in industrial food processing equipment. It is compulsory to remove as many organisms as possible before disinfection. Biocides are used frequently for cleaning the cooling systems/apparatus. Chlorinated alkaline detergents followed by non-chlorinated ones are used frequently since acid products showed to be no more effective than warm water usage. To eliminate *Acinetobacter* sp., a higher pH (12) completely removes almost 100 times more bacterial strains than obtained at a lower pH of 2 [2, 3]. Peracetic acid has been used for a long time as a disinfectant. It was predominantly used in conditions where silicon pipes are filled with bacterial biofilms, and a continuous flow of tap water passes through it. The same is immensely effective than other chemical compounds like aldehydes, hydrogen peroxide, and chlorine. However, soon it was found that biofilms were still present upon observation in scanning electron microscopes (SEM). In this situation, hydrogen peroxide (H_2O_2) treatment comes under the picture. Other detergents include sodium hypochlorite and ozone.

Table 2 Bacterial species along with the proteins secreted during biofilm formation

Name of the microorganism	Proteins secreted	Functions	References
S. aureus	Biofilm associated proteins (bap)	Formation of biofilms and their adhesion to the host cells	[13]
B. subtilis	Single major amyloid protein: TasA	Strong filers of TasA hold biofilm cells rigidly, tolerate harsh destructive forces	[14]
P. aeruginosa	Galactophillic lectin LecA and L-fucose binding lectin LecB	Helps in stabilizing the biofilm matrix	[15]
S. mutans	Glucan-binding proteins (Gbps)	Links bacteria and the EPS, maintains bacterial architecture, assists in sucrose dependant biofilm formation	[16]
Pseudomonas spp.	Fap amyloids	Cellular aggregation, increased formation of biofilms	[17]
E. faecalis	Esp proteins	Primary adhesion on abiotic surfaces	[18]
Actinobacillus pleuropneumonia	DspB protein	Surface detachment, initiating a new biofilm lifecycle	[19]

Moreover, it is essential to maintain a clean and dry environment since moisture will enhance biofouling. It can be achieved by a method known as Cleaning-In-Place (in situ). The entire system is cleaned by turbulent spraying the whole plant throughout the surface and inside without manual operation. Its efficiency can be increased by adding caustic and nitric acid [7, 8].

Bioelectric Devices

Bacterial contamination in bioelectric devices, prosthetics, and other internally placed medical devices causes fatal infections and life-threatening diseases. Moreover, it also causes device failures, high mortality, and high morbidities. These bioelectric devices play an essential role in the biomedical field, from biomarker sensing to curing complex diseases like cancer, epilepsy, kidney, and heart failures. They work under rigorous fluidic environments. Thus, it is necessary to protect these devices from fouling since the replacement and treatment of infections from these device implants is costly. Physical strategies for preventing biofilm formation include manual cleaning and coating the devices with hydrophilic polymers such as hyaluronic acid and poly-N-vinylpyrrolidone which were primarily used in coating the surface of catheters. Hydrogel and heparin coatings that can uptake and release antibiotics have been increasingly used to prevent surface adhesion of various microorganisms.

Chemical strategies involve polyethylene glycol (PEG), phosphorylcholine (PC), and the usage of other chemicals like polyoxazolines, polysaccharides, poly(hydroxy acrylates), and hyperbranched polyglycerol (HPG). Organic tin and its derivatives have also found prominence since the last twentieth century. It includes tributylin oxide and tributyltin fluoride. These happen to be extremely powerful fungicides and ultimately inhibit most fouling microorganisms' growth using low concentrations.

Biological approaches rely on affinity binding, which acts selectively and prevents EPS formation and depletes foulants before reaching the surface. It uses enzymatic catalysis as a destroy mechanism. A surface is considered resistant to fouling when it allows a level of less than 1000 pg/mm^2. Various approaches have also been made inspired by nature or biomimicry. Naturally occurring self-polishing coatings made from pilot whale skin have been used, which helps hydrolyze seawater and create a foulant-free surface. Temperature responsive coatings like poly-N-isopropylacryl-amide (pNIPAm) also brush control hydrogen bonding and further matrix developments. Hydrogel coatings are also used to remove any aggregated biofilm matrices. Other layers involve phospholipid coatings, Nafion-based antifouling coatings, pH resistant coatings, covalent organic frameworks, diamond-like carbon coatings, and modifying and creating biomimetic surfaces (lotus flower surfaces, shark skin, rice leaf, butterfly wings) [20].

Medical Devices

Some of the commonly occurring refractory bacterial diseases are involved with medical devices. These include prosthetic heart valves or cardiac instrumentations, pacemakers, various kinds of catheters, vascular grafts, and intrauterine devices. Biofilms formed on medical devices are primarily composed of yeast or bacteria found in patients' skin, contaminated water, or regular tap water where the infection-prone device is used. The bacteria associated with contaminating medical devices are *Enterococcus faecalis*, *Staphylococcus aureus*, *S. epidermis*, *Streptococcus viridians*, *E. coli*, *P. mirabilis*, *K. pneumoniae*, and *P.*

aeruginosa. Moreover, two-thirds of the human infections from bacteria are derived from biofilms. In the present survey, some of them are picked.

Urinary Catheters

Typically, three types of catheters are used in the medical field, i.e., uncoated, polymer-coated, and antimicrobial coated. The uncoated catheter could be made of latex, silicone, or a combination of both. Latex is unsuitable for allergic people. Therefore, silicone ones are used, proven to be 100% safer but more costly. Catheters that are presently utilized have nitrofurazone or silver coating on them. Nitrofurazone releases the drug in the urethral tract environment, reducing infection of broad-spectrum bacteria and urinary tract (UTI). Silver alloy-layered catheter prevents infection and decreases the average CUTI from 25 to 47% in over 30 scientific clinical trials. Other external coatings proven effective against biofilms are hydrogel on silicon for *S. epidermidis*, ciprofloxacin hydrogel, etc. Often biocides are used as in vitro models, like triclosan and farco-fill (Farco-fill®), to reduce *P. mirabilis* infection. It was also used to minimize encrustation in almost 40% of the tested patients. In other studies, urease enzymes were controlled, a significant component for biofilms. Moreover, bacteriophages have also been used since they have bactericidal properties [20, 21, 22]. In the recent times, thin film magnetic actuators have been used in catheters to prevent the formation of protein-based biofilms [23]. Other researches include covalent mucin coatings, conformal hydrogel coatings, chrysophanol functionalism nanoparticles made of silver, and surface modification with the help of dopamine-hyaluronic acid conjugate [24, 25, 26, 27].

Preventive Measures and Maintenance Against Biofouling

Several additives have been used as effective antibacterial agents for sterilizing food processing equipment, i.e., colourants, flavours, and surfactants. Meniscus pigments prevent *E. coli* contamination at a minimum inhibitory concentration of 2.5 mg/mL. Surfactants like sucrose fatty acid esters have successfully prevented biofilm formation in *B. cereus*, *B. subtilis*, *S. aureus*, *S. typhimurium*, *E. coli*, etc. Food additives are also said to possess anti-biofilm activity under specific conditions. For example, the bioengineered derivative of Nisin A in combination with citric acid or *Cinnamaldehyde* is said to eradicate the formation of *L. monocytogenes* biofilms. Several researchers have also shown that a wide variety of Chinese traditional medicine aid in quorum sensings like emodin, radix scutellaria, and rhubarb can improve the antibacterial effects when combined with penicillin, gentamicin, etc. [8, 28]. Anti-biofilm enzymes mainly work by attacking the EPS matrix surrounding the cells. The mode of action, however, varies. The enzymes can attack the biofilm directly, promote cellular lysis, catalyze the antimicrobial formulations, or interfere with the quorum sensing mechanisms. Four enzymes primarily take charge of this process, i.e., anti-QS, polysaccharide, proteolytic, and oxidative enzymes. All of which belong to the class hydrolase oxidoreductase and lyases.

Anti-QS Enzymes

Lactonases help hydrolyze the bond present in the homoserine ring, thus preventing the AHLs (N-acylhomoserine lactone) from binding to transcriptional regulators. This method

caused an overall 69 to 78% reduction in biofilm formation by *P. aeruginosa* and its virulence factors. In another study, lactose obtained from the T7 bacteriophage had a broad range of activity for QS inhibition in *E. coli* and *P. aeruginosa* on poly vinyl chloride (PVC) microtiter plates.

Proteolytic Enzymes

One of the most efficient enzymatic preparations of proteolytic enzymes made is Savinase® which successfully removed *Pseudomonas fluorescens* and *Pseudoalteromonas* sp. biofilms. Pandion, paradigm, resinase, and spezyyme enzymes, when applied individually for 30 min, attained a 4 log reduction of *P. aeruginosa*. Moreover, bacteriophages and engineered bacteriophages (with the help of synthetic biology) are also used to disrupt the EPS matrix since they cause bacterial infection and promote lysis. One such application was the reduction of *E. coli* strain O157:H7 in low populations (2.8 log CFU per stainless steel coupon) which developed for 24 h at 22°C. Enzymes like DNase helps to reduce biofouling in microorganisms like *Enterococcus faecalis*, *Streptococcus pneumoniae*, and *Listeria* sp. [28].

EPS Degrading Enzymes

Amylase, lyase, cellulase, alginate, and lysozyme are among the enzymes that successfully degrade the EPS present on the matrix. Cellulase has the potential of efficiently degrading the EPS of *P. aeruginosa*. Another enzyme, α-amylase, could decrease biofilms formed by *Staphylococcus aureus* approximately to 79% [8, 9, 28].

Many times, a combination of enzymes are also used. For example, applying cellulase followed by pronate to *P. fluorescens* on borosilicate glass surfaces removed 94% of the biofilms. Chemical and physical treatments are often merged with these enzymes to increase the efficiency of anti-biofouling. A combination of enzymes, including amyloglucoside, lysozyme, papain, protease, and trypsin, was linked with ultrasounds (40 kHz for 10 s) with a chelating agent EDTA for removing biofilms present on stainless steel surfaces. Acylase-I (100 µg/mL) and proteinase K (5 µg/15 mL) were used for the removal of 33.7% of the cells that is present in a reverse osmosis membrane [8, 28].

Conclusion

Biofilms and biofouling are a severe threat to the environment since they cause thoughtful infections, and the prevention of the same is a rapidly growing and active domain of research. Breaking down a mature biofilm or combating infection is challenging; thus, cell-repellant technologies and protecting the surface from an infestation are critical. The cells embedded in the biofilm carry much potential for further infection and are less susceptible to external antibiotics or antimicrobial agents. Thus, preventions using antimicrobial coatings, surface modification by biomimicry, and combined chemical processing are increasingly used to prevent spreading and colonization. Since a significant setback to the anti-biofilming procedures is the ineffectiveness of existing antibiotics, there is a constant need to resort to advanced technologies. Some advances are QS technologies, surface modification by engineered polymers, surface grafting using small molecules, surface coatings, and cell-repellant methods. These are increasingly used, which ultimately will combat host

tissues. Newer insights are required as very little literature focuses on the overall antifouling engineering across various fields, some of which has been covered here as compared to others. Moreover, abundant research is needed in the antifouling strategies for combating biofouling in food industries and medical equipments.

Author Contribution All authors contributed to the study conception and design. IJ and SD performed material preparation, data collection, and analysis. IJ wrote the first draft of the manuscript. All authors read and approved the final manuscript.

Data Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable (as no animal or human work is concerned).

Competing Interests The authors declare no competing interests.

References

1. Costerton, J. W., Cheng, K. J., Geesey, G. G., Ladd, T. I., Nickel, J. C., Dasgupta, M., & Marrie, T. J. (1987). Bacterial biofilms in nature and disease. *Annual Reviews in Microbiology, 41*(1), 435–464.
2. Carpentier, B., & Cerf, O. (1993). Biofilms and their consequences, with particular reference to hygiene in the food industry. *Journal of Applied Bacteriology, 75*(6), 499–511.
3. Anwar, H., van Biesen, T., Dasgupta, M., Lam, K., & Costerton, J. W. (1989). Interaction of biofilm bacteria with antibiotics in a novel in vitro chemostat system. *Antimicrobial Agents and Chemotherapy, 33*(10), 1824–1826.
4. Rabin, N., Zheng, Y., Opoku-Temeng, C., Yixuan, Du., Bonsu, E., & Sintim, H. O. (2015). Biofilm formation mechanisms and targets for developing antibiofilm agents. *Future Medicinal Chemistry, 7*(4), 493–512.
5. Simmons, W. L., Bolland, J. R., Daubenspeck, J. M., & Dybvig, K. (2007). A stochastic mechanism for biofilm formation by *Mycoplasma pulmonis*. *Journal of Bacteriology, 189*(5), 1905–1913.
6. Armbruster, C. R., & Parsek, M. R. (2018). New insight into the early stages of biofilm formation. *Proceedings of the National Academy of Sciences, 115*(17), 4317–4319.
7. López, D., Vlamakis, H., & Kolter, R. (2010). Biofilms. *Cold Spring Harbor Perspectives in Biology, 2*(7), 000398.
8. Zhao, X., Zhao, F., Wang, J., & Zhong, N. (2017). Biofilm formation and control strategies of foodborne pathogens: Food safety perspectives. *RSC advances, 7*(58), 36670–36683.
9. Allison, D. G., & Gilbert, P. (1995). Modification by surface association of antimicrobial susceptibility of bacterial populations. *Journal of Industrial Microbiology, 15*(4), 311–317.
10. Marvasi, M., Visscher, P. T., & Casillas Martinez, L. (2010). Exopolymeric substances (EPS) from *Bacillus subtilis*: Polymers and genes encoding their synthesis. *FEMS Microbiology Letters, 313*(1), 1–9.
11. Franklin, M. J., Nivens, D. E., Weadge, J. T., & Howell, P. L. (2011). Biosynthesis of the *Pseudomonas aeruginosa* extracellular polysaccharides, alginate, Pel, and Psl. *Frontiers in Microbiology, 2*, 167.
12. Vuong, C., Voyich, J. M., Fischer, E. R., Braughton, K. R., Whitney, A. R., DeLeo, F. R., & Otto, M. (2004). Polysaccharide intercellular adhesin (PIA) protects *Staphylococcus epidermidis* against major components of the human innate immune system. *Cellular Microbiology, 6*(3), 269–275.
13. Cucarella, C., Tormo, M. A., Ubeda, C., Trotonda, M. P., Monzón, M., Peris, C., Amorena, B., Lasa, Í., & Penadés, J. R. (2004). Role of biofilm-associated protein bap in the pathogenesis of bovine *Staphylococcus aureus*. *Infection and Immunity, 72*(4), 2177–2185.

14. Vogt, C. M., Schraner, E. M., Aguilar, C., & Eichwald, C. (2016). Heterologous expression of antigenic peptides in *Bacillus subtilis* biofilms. *Microbial Cell Factories, 15*(1), 1–12.
15. da Silva, D. P., Matwichuk, M. L., Townsend, D. O., Reichhardt, C., Lamba, D., Wozniak, D. J., & Parsek, M. R. (2019). The *Pseudomonas aeruginosa* lectin LecB binds to the exopolysaccharide Psl and stabilizes the biofilm matrix. *Nature Communications, 10*(1), 1–11.
16. Lynch, D. J., Fountain, T. L., Mazurkiewicz, J. E., & Banas, J. A. (2007). Glucan-binding proteins are essential for shaping *Streptococcus mutans* biofilm architecture. *FEMS Microbiology Letters, 268*(2), 158–165.
17. Rouse, S. L., Matthews, S. J., & Dueholm, M. S. (2018). Ecology and biogenesis of functional amyloids in *Pseudomonas*. *Journal of Molecular Biology, 430*(20), 3685–3695.
18. Toledo-Arana, A., Valle, J., Solano, C., Arrizubieta, M. J., Cucarella, C., Lamata, M., Amorena, B., Leiva, J., Penadés, J. R., & Lasa, I. (2001). The enterococcal surface protein, Esp, is involved in *Enterococcus faecalis* biofilm formation. *Applied and Environmental Microbiology, 67*(10), 4538–4545.
19. Kaplan, J. B., Velliyagounder, K., Ragunath, C., Rohde, H., Mack, D., Knobloch, J. K. M., & Ramasubbu, N. (2004). Genes involved in the synthesis and degradation of matrix polysaccharide in *Actinobacillus actinomycetemcomitans* and *Actinobacillus pleuropneumoniae* biofilms. *Journal of Bacteriology, 186*(24), 8213–8220.
20. Chen, X., & Noy, A. (2021). Antifouling strategies for protecting bioelectronic devices. *APL Materials, 9*(2), 020701.
21. LoVetri, K., Gawande, P.V., Yakandawala, N. and Madhyastha, S. (2010). Biofouling and antifouling of medical devices. Biofouling types, Impact and Antifouling, 105–128
22. Pelling, H., Nzakizwanayo, J., Milo, S., Denham, E. L., MacFarlane, W. M., Bock, L. J., Sutton, J. M., & Jones, B. V. (2019). Bacterial biofilm formation on indwelling urethral catheters. *Letters in Applied Microbiology, 68*(4), 277–293.
23. Yang, Q., Park, H., Nguyen, T. N., Rhoads, J. F., Lee, A., Bentley, R. T., Judy, J. W., & Lee, H. (2018). Anti-biofouling implantable catheter using thin-film magnetic microactuators. *Sensors and Actuators B: Chemical, 273*, 1694–1704.
24. Winkeljann, B., Bauer, M. G., Marczynski, M., Rauh, T., Sieber, S. A., & Lieleg, O. (2020). Covalent mucin coatings form stable anti-biofouling layers on a broad range of medical polymer materials. *Advanced Materials Interfaces, 7*(4), 1902069.
25. Yong, Y., Qiao, M., Chiu, A., Fuchs, S., Liu, Q., Pardo, Y., Worobo, R., Liu, Z., & Ma, M. (2018). Conformal hydrogel coatings on catheters to reduce biofouling. *Langmuir, 35*(5), 1927–1934.
26. Prateeksha, P., Bajpai, R., Rao, C. V., Upreti, D. K., Barik, S. K., & Singh, B. N. (2021). Chrysophanol-functionalized silver nanoparticles for anti-adhesive and anti-biofouling coatings to prevent urinary catheter-associated infections. *ACS Applied Nano Materials, 4*(2), 1512–1528.
27. Lee, S., Kim, S., Park, J., & Lee, J. Y. (2020). Universal surface modification using dopamine-hyaluronic acid conjugates for anti-biofouling. *International Journal of Biological Macromolecules, 151*, 1314–1321.
28. Meireles, A., Borges, A., Giaouris, E., & Simões, M. (2016). The current knowledge on the application of anti-biofilm enzymes in the food industry. *Food Research International, 86*, 140–146.