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SURFACE MODIFIERS FOR REDUCING BACTERIAL CONTAMINATION IN MEDICINE AND FOOD INDUSTRY

© 2025 Y. V. Cherednichenko*, I. R. Ishmukhametov, and G. I. Fakhrullina

Institute of Fundamental Medicine and Biology, Kazan Federal University, Kazan, Russia

**e-mail: serova.yuliya87@gmail.com*

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Abstract. Antibacterial coatings are used in the food and textile industries, in the construction industry, in biotechnology and medicine. The review considers the main types of coatings that prevent fouling with biomacromolecules and microorganisms: anti-adhesive, contact, release-based, multifunctional and intelligent ("smart") coatings. For each type of coating, the most relevant and effective active substances and their mechanism of action are described. Despite the widespread use of anti-adhesive surfaces and contact coatings, they have many disadvantages that limit the scope of their application and reduce activity and durability. Numerous studies show that multifunctional and intelligent coatings have high potential for practical application and further research on their modification to obtain universal and cost-effective coatings. The main problem of the practical application of such surfaces is the imperfection of methods for assessing the stability and antibacterial properties of the coating in laboratory conditions.

Keywords: *antibacterial coatings, contact, release-based, anti-adhesive, multifunctional, intelligent*

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INTRODUCTION

The original role of surface coatings in industrial applications was to provide corrosion protection and mechanical resistance of materials [1]. Recently, there has been great interest in developing surfaces that reduce microbial adhesion and provide biocidal activity or exhibit combined effects [2–5]. Antimicrobial coatings are materials and substances that modify the surface of another material and give them functions that limit or prevent the growth and multiplication of microorganisms without changing the characteristics of the material itself [6, 7]. To create such coatings, various physical and chemical methods are used to ensure the formation of homogeneous layers. For coatings to be effective, they must include active compounds with a wide range of antimicrobial activity, including antibiotic-resistant microorganisms [8].

Bacterial resistance to antibiotics is one of the most important problems of modern medicine. Bacterial strains can modify the targets of antibiotic action, inhibit the penetration and active excretion of antibiotics from the microbial cell (efflux), form metabolic "shunts", and produce enzymes that destroy antimicrobial drugs [9, 10]. A particularly alarming factor is the ubiquity of bacterial strains with multiple resistance to antimicrobial agents, as well as the ability of microorganisms to form biofilms [11]. Bacterial biofilms are aggregations of bacteria in a self-secreted polymer matrix. They are formed both on biological and non-biological surfaces and are an important step in the emergence of persistent infections. Within the biofilm, microbes have increased resistance to immune system factors, antibiotics and disinfectants [12]. The matrix of bacterial biofilms slows down the diffusion of antibiotics, and changes in the chemical microenvironment within the biofilm leads to the formation of persistent forms of bacteria that have increased resistance to antimicrobial agents [13, 14]. Therefore, to combat antibiotic resistance, it is necessary to search for new antibacterial agents that would be effective against isolated bacterial strains and bacterial communities forming biofilms.

The development and creation of coatings with antimicrobial properties is of great practical importance and finds application in various fields [15–17]. For example, food packaging systems containing antimicrobial agents can be used not only to reduce the number of pathogens, but also to combat microorganisms that cause food spoilage [18]. Such packaging isolates food from the environment and suppresses microbial growth without affecting its composition [19]. Due to the

slow and/or controlled release of antibacterial agents, their inhibition during transportation and storage is ensured, which increases the shelf life of foods [20, 21]. In healthcare facilities, antimicrobial coatings are used as a modern hygienic method to control bacterial contamination [22–24]. Current coatings against bacterial fouling and contamination are capable of: controlling pathogen populations on surfaces and minimizing the risks of resistance to their constituent antimicrobial agents; being stable and (eco)toxicologically safe; affordable and easily implemented in hospital settings [25–27]. Recent advances in the architectonics of nanomaterials have led to the emergence of antibacterial nanoparticles, which can be useful in the textile industry to enhance the antibacterial properties of fabrics, control the spread of pathogenic bacteria and associated infections among humans, and safe for human health and the environment. Such nanoparticles are introduced into the surface of the fabric by plasma technique, laser treatment, cationization, and by functionalizing or modifying the surface of the textile. Moreover, biosensor nanoparticles are embedded into the fabric to monitor human disease states [28–30]. The antimicrobial properties of materials are used in the construction of institutions where high standards of hygiene are required to prevent the formation of bacterial biofilms, mold and mildew, and to protect structures from biodegradation [31, 32]. Antimicrobial agents are introduced by applying paint or coating to the finished surface after construction, by mixing inorganic additives (metal nanoparticles, metal oxides) with concrete or mortar during construction and by mixing antimicrobial agents during the manufacture of building materials [33]. The creation of a protective layer, in the form of a paint or coating, which is active against a wide range of microorganisms and stable over a wide pH range is more demanded in the construction field [34–36].

Thus, modern antibacterial coatings in the medical and food industries must meet such criteria as: efficiency, safety and durability. The review considers the main types of existing antibacterial coatings, mechanisms of action of coatings and their constituent components. Advantages and disadvantages for further design of future antimicrobial materials are evaluated.

TYPES OF ANTIBACTERIAL COATINGS

Over the past two decades, the attention of scientists and biomedical manufacturers has been focused on the development of coatings capable of resisting bacterial colonization that could be applied to various surfaces and devices [37, 38]. Antimicrobial coatings (Fig. 1), depending on their mechanism of action, are divided into: contact-type antimicrobial coatings [39–41] and release-based coatings, anti-adhesive antimicrobial coatings [42–45], multifunctional coatings [46–48], and smart antimicrobial coatings [49–51].

Earlier designs of antibacterial coatings for the strategy of preventing bacterial adhesion and subsequent biofilm formation were mostly monofunctional. They were based on the antibacterial effect inactivating microorganisms in contact with the surface or preventing their attachment [52, 53]. The first in this field were coatings with copper oxide, arsenic, mercury oxide and organoleaf derivatives that prevented biofouling of marine vessels [54, 55]. Since 1906, the development of anti-corrosion and anti-fouling paints for marine vessels based on zinc oxide and mercury oxide began [56]. In 1954 G.J.M. Der Van Kerk and J.G.A. Luijten showed biocidal properties of organotin compounds [57], which later became widespread as effective antifouling coatings. In 1995, polyurethane films containing quaternary ammonium compounds were developed, showing high biocidal activity against *Escherichia coli* [58] and polymer coatings modified with silver nitrate, which showed antibacterial effect against *Staphylococcus epidermidis* [59]. Lowe A.B. et al. in 2000 described a statistical copolymer of butyl acrylate with sulfobetaines, which when adsorbed on plastic disks reduced the adhesion of *Pseudomonas aeruginosa*, macrophages and fibroblasts [60].

Current coatings against bacterial contamination and fouling, focus on the synergistic combination of antibacterial and anti-adhesion effects in the form of multifunctional, smart coatings or interfacial materials [61]. The first example of a smart coating consisting of zwitterionic polymer derivatives that can rapidly switch their chemical structures and possess antibacterial, anti-adhesive properties and self-cleaning ability was described by Cheng G. et al., 2008 [62]. Subsequently, nanostructured coatings composed of temperature-sensitive poly N-isopropylacrylamide and quaternary ammonium salt were prepared by interferometric lithography and surface polymerization, which exhibit biocidal properties and the ability to release inactivated bacteria in response to temperature changes [63]. In 2018, a hybrid film was fabricated by successive deposition of a layer of gold nanoparticles and a phase transition lysozyme film, which had bactericidal activity under near-infrared laser irradiation, and its immersion in vitamin C promoted the removal of killed bacteria and surface regeneration [64]. In recent years, machine learning methods have been actively introduced in the development of various coatings. In 2021, a machine learning method (using an artificial neural network model and a model based on support vector regression) was developed to synthesize new anti-adhesive polymer brushes that demonstrated excellent resistance to protein adsorption at optimal film thickness [65].

Contact-type antibacterial coatings and antibacterial release coatings

Bactericidal coatings provide a reliable and simple way to prevent biofilm formation by exerting a biocidal effect on bacteria attached to the surface or suspended near the surface [5]. They are based on the introduction of antibacterial agents into the material or on its surface,

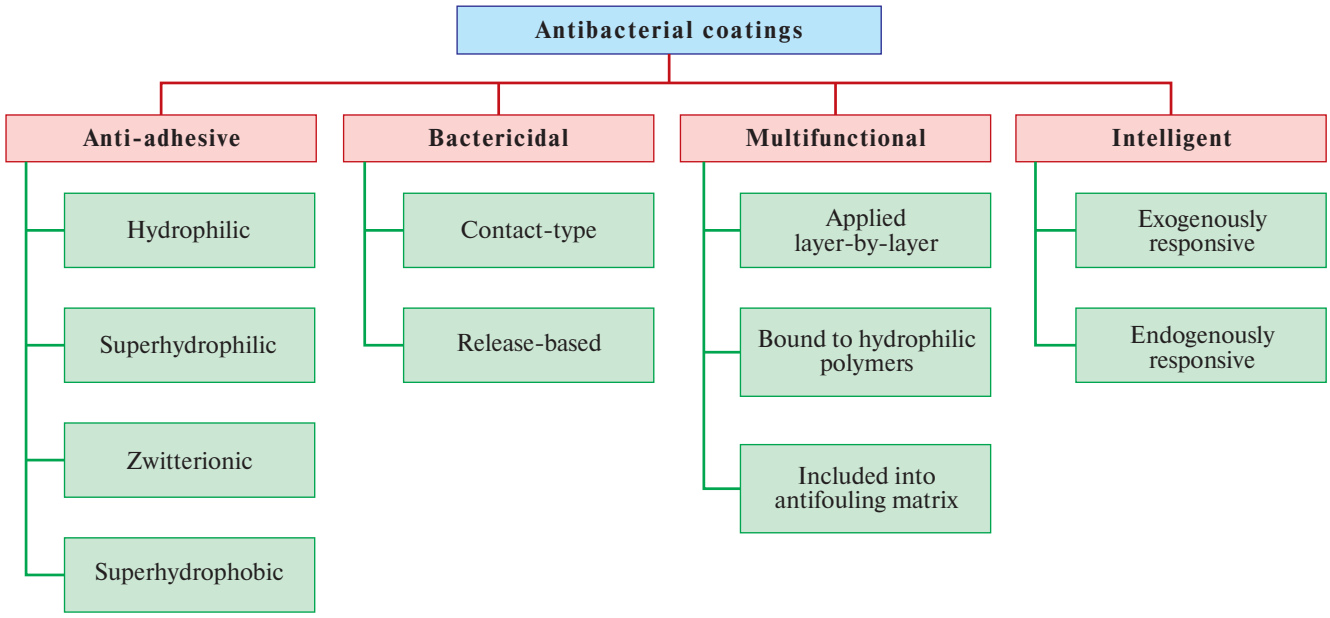

Fig. 1. Classification of the main types of antibacterial coatings.

which through gradual release of agents (Fig. 2b) or contact action (Fig. 2a) inactivate, damage or inhibit bacterial growth [66, 61]. Different biocides are fixed on the surface by dipping the coating in antimicrobial agent, spraying and centrifugation, and using layer-by-layer application technique or surface modification with different polymers [52]. Contact coatings can be divided into inorganic and organic coatings. Inorganic antimicrobial coatings are represented by nanoparticles of metals and their oxides (Ag, Au, Zn, Mg, and Cu) [67] and antibiotics (aminoglycosides, quinolones, penicillins, glycopeptides, tetracyclines, rifamycins) [68]. Organic antimicrobial coatings, are represented by quaternary ammonium salts (QAS) [69] and natural organic substances (antimicrobial peptides (AMP), enzymes and polysaccharides (chitosan)) [70–72]. Metal nanoparticles and their oxides are effective antibacterial agents because they can penetrate bacterial cells through ion channels and trigger the Fenton reaction with the formation of excess reactive oxygen species, increase bacterial cell wall permeability and oxidative stress in the bacterial cell body; can form secondary toxic metabolites, affecting the metabolic activity of bacteria; and induce changes in bacterial genetic information (e.g., 16S rDNA) [73]. Coatings, releasing antibiotics are able to deliver them directly to the site of action, thus providing higher efficacy and avoiding high dose antibiotic administration, systemic toxicity and development of drug resistance [74]. Antibiotics can inhibit bacterial cell protein synthesis, DNA replication and transcription by acting on DNA topoisomerases II and IV or by binding to RNA polymerase, disrupt cell wall peptidoglycan synthesis by enzymatic inhibition or by binding to amino acids [75, 76]. AMPs (Fig. 2c) are considered a promising candidate to replace conventional antibiotics because of their broad spectrum and nonspecific antibacterial mechanism of action [77]. They attach to the surface of the bacterial cell membrane, resulting in various forms of membrane damage; interfere with DNA and RNA synthesis and inhibit enzyme activity, causing bacterial death. In addition, AMPs exhibit excellent antibiofilm activity. Cationic molecules (e.g., QASs) can effectively kill bacteria through contact killing effect [78]. They can first adsorb on the bacterial cell wall through electrostatic action and then diffuse inward by disrupting the membrane potential, resulting in membrane damage, cytoplasmic leakage and bacterial death [73]. Chitosan and its derivatives exhibit antibacterial activity against fungi, Gram-positive and Gram-negative bacteria. The antibacterial activity of this polymer may be due to the interaction of amino groups of chitosan with the electronegative charges of the bacterial cell surface, resulting in the leakage of intracellular components [79]. It also exhibits biodegradability, biocompatibility, polymorphism and sorption properties [80]. Antibacterial enzymes are able to directly attack the microorganism, inhibit biofilm formation, degrade the biofilm, and/or catalyze reactions that lead to the production of antimicrobial compounds [81]. Release-based surfaces exhibit their antibacterial activity by releasing antibacterial agents by diffusion, erosion, degradation, or hydrolysis of covalent bonds into the environment [82]. The compounds are released from the surface of the material and the antibacterial activity occurs locally, only where it is needed. Depending on the antibacterial agent incorporated in the matrix, release-based coatings are capable of releasing antibiotics (penicillin, chlortetracycline, streptomycin, vancomycin), metal ions and oxides (Ag, Zn, and Cu) and non-metallic materials, fluorine (F) [83, 84, 27]. Polymethacrylic acid, polyacrylic acid, lactic and glycolic acid-based copolymers, hydroxyapatite, polyurethane, hyaluronic

acid, chitosan, and ceramic nanoparticles are used as a carrier in such surfaces. Antibacterial release based surfaces are prepared by impregnating a porous material or coating with the desired antibacterial compound, by layer-by-layer application or by plasma spraying of polyelectorlites [85, 86, 52].

The main disadvantages of such coatings are the limited supply of antibacterial agents, which make the coatings unusable once they are depleted, and the toxicity of some antibacterial agents (QASs, nanoparticles and metal ions). Nanoparticles penetrate cells and subsequently exert toxic effects on intracellular structures. They cause mitochondrial damage, oxidative stress and autophagy [87, 88], and in high concentrations, cell necrosis and apoptosis [89]. Metal oxides (ZnO, MgO, CuO) are also cytotoxic and cause apoptosis, autophagy, oxidative stress and necrosis [90]. The accumulation of inactivated bacteria and intracellular components not only reduces coating efficacy, but can also promote biofilm formation [61] and induce immune reactions or inflammation. In addition, most biocidal agents are positively charged and can interact electrostatically with proteins. Moreover, different biocidal methods are based on different killing mechanisms and each method is effective for a specific type of bacteria. With the emergence of multidrug-resistant bacterial strains, approaches using a single killing mechanism are becoming less effective [5]. For example, silver-based materials have a strong bactericidal effect, but their activity decreases over time as the coatings continuously release the biocidal agent. In the case of polycationic polymer-based coatings, surface treatment with a cationic surfactant may be required to restore antimicrobial activity. Low molecular weight bactericidal agents often cause resistance and gradually lose their effectiveness over time [91].

Anti-adhesion antimicrobial coatings

Surface characteristics of materials, including surface charge, free energy, morphology, wettability, etc., have an important influence on bacterial adhesion [92]. Bacteria can attach to various surfaces and form biofilms through non-specific interactions such as hydrogen bonds, electrostatic forces, hydrophobic interactions, and van der Waals forces (Fig. 3a). Thus, bacterial adhesion on the surface of implanted devices contributes to device-associated infections and is the main reason for the development of anti-adhesion coatings [93]. To prevent the development of biofilms on biomaterial surfaces, the surface must be able to prevent initial bacterial adhesion [22]. Anti-adhesion coatings are functional coatings created by modifying the surface of materials by changing their physicochemical properties (roughness, degree of wettability, charge, etc.), which prevents the adhesion of bacteria, fungi and proteins (Fig. 3b) [94]. The action of such coatings is based on steric, electrostatic and superhydrophobic effects, which can be observed on hydrophilic, superhydrophilic, charged and superhydrophobic surfaces, respectively (Fig. 3c) [52]. Hydrophilic surfaces prevent the attachment of cells and bacteria due to the fact that they are covered by a layer of water molecules that are closely hydrogen bonded to the hydrophilic material and act as a physical and energetic barrier that must be overcome for adsorption. Hydrophilic polymers can also inhibit bacterial attachment to some extent, but high antifouling properties are acquired only when steric repulsion complements surface hydration [95]. Thus, highly hydrated polymers such as polyethylene glycol (PEG), neutral and hydrophilic polymers poly(2-alkyl-2-oxazoline) have demonstrated the ability to reduce bacterial and protein adhesion through steric hindrance [96, 97]. Hydrophilic coatings are prepared by physical, chemical adsorption, direct covalent attachment and block or grafted copolymerization [98]. Laser treatment of metal-based coatings with antibacterial properties makes it possible to obtain superhydrophilic coatings. In the zone of laser beam exposure the surface is heated and melting, sublimation and explosive ablation of the material takes place. At the same time, metal particles are removed from the surface and subsequently deposited, forming a micro-relief around the impact zone in the form of micro- and nanoparticles. Due to the high wettability of superhydrophilic coatings, the contact area is increased and metal ions from the formed nanoparticles are more efficiently transported into the liquid causing oxidative stress of bacterial cells. In addition, the formation of hierarchical surface porosity leads to bacterial death as a result of perforation and deformation of the membrane by the nanotexture elements and loss of intracellular fluid [99–101]. Compared to hydrophilic polymers, the interaction of bound water through ionic solvation is stronger than the hydrogen bonded water layer, which enhances the antifouling nature of zwitterionic surfaces [102]. Surfaces functionalized with zwitterionic polymers, which have a uniform distribution of anionic and cationic groups along their main chain in their structure, exhibit antifouling properties. These include polymethacryloyloxyethyl phosphorylcholine, polysulfobetainmethacrylate and polysulfobetainacrylamide as they contain cationic quaternary ammonium salt on the one hand and anionic carboxylate, phosphate and sulfate groups on the other hand, respectively [103]. In addition to the steric hindrance effect of this hydration layer, the cationic groups can also kill bacteria on contact. In addition, the surfaces functionalized with zwitterionic polymers are more versatile and stable regardless of temperature and salt concentration than PEG functionalization. Consequently, these polymers are widely used as antibacterial coatings [104]. Superhydrophobic surfaces have attracted much attention for their excellent self-cleaning properties and potential applications in various industries [105]. The water contact angle of such surfaces exceeds 150° and hence they are difficult to wet. The superhydrophobicity reduces the adhesion force between bacteria and the surface and facilitates the removal of

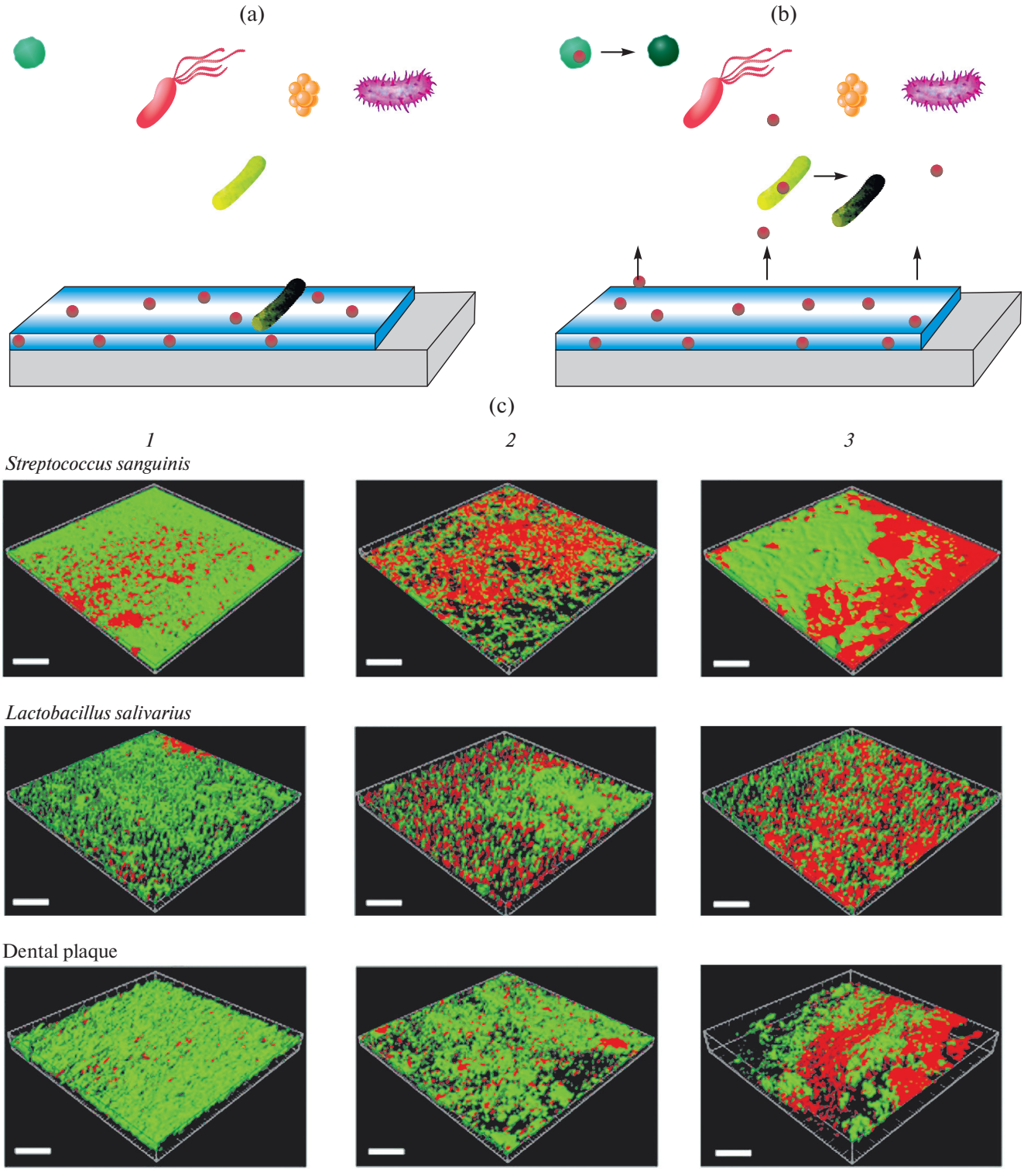

Fig. 2. a – Schematic representation of the mechanism of action of contact-type antibacterial coatings; b – Schematic representation of the mechanism of action of antibacterial coatings based on release; c – Images of viable cells (green) and dead bacteria (red) of *S. sanguinis*, *L. salivarius* and dental plaque obtained by confocal microscopy with 20x objective magnification after 4 weeks of incubation at 37°C (*1*) on titanium surface, (*2*) on titanium surface with silver electrodeposition, (*3*) on titanium surface coated with silane triethoxysilylpropylantharic anhydride, with immobilized hLf1-11 peptide. Reproduced from [39], with permission of the American Chemical Society, 2015.

initially adhered bacteria before biofilm formation [106, 52, 22]. This phenomenon is attributed to two physical principles: low surface energy and rough structures at the microscopic scale. Chemistry and surface topography are the main factors that interfere with interactions at the liquid–solid interface. Surface energy affects the adhesion of substances to the interface, including liquids and microorganisms. Low surface energy reduces the work of adhesion and hence increases hydrophobicity [107]. Superhydrophobic surfaces are achieved by preparing micro/nanostructures and then passivating them with low surface energy molecules [7]. The methods to obtain superhydrophobic antifouling coatings include chemical and physical etching, immersion method, sol-gel method, chemical vapor deposition, photolithography, centrifugation, electrospinning, layer-by-layer deposition, and/or a combination of these [108]. However, superior durability of functional properties for such surfaces is demonstrated by the laser texturing method [109, 110].

Antifouling coatings only prevent bacterial adhesion, not eliminate it (Fig. 3d). Therefore, over time there is an increase in the concentration of planktonic bacteria in the substrate, which contributes to bacterial contamination and leads to infections. In addition, hydrophilic polymers can be gradually neutralized, passivated or degraded by other compounds such as proteins, salts and amphiphiles. Any localized defects in superhydrophobic coatings can act as local adhesion sites for bacteria with subsequent biofilm formation.

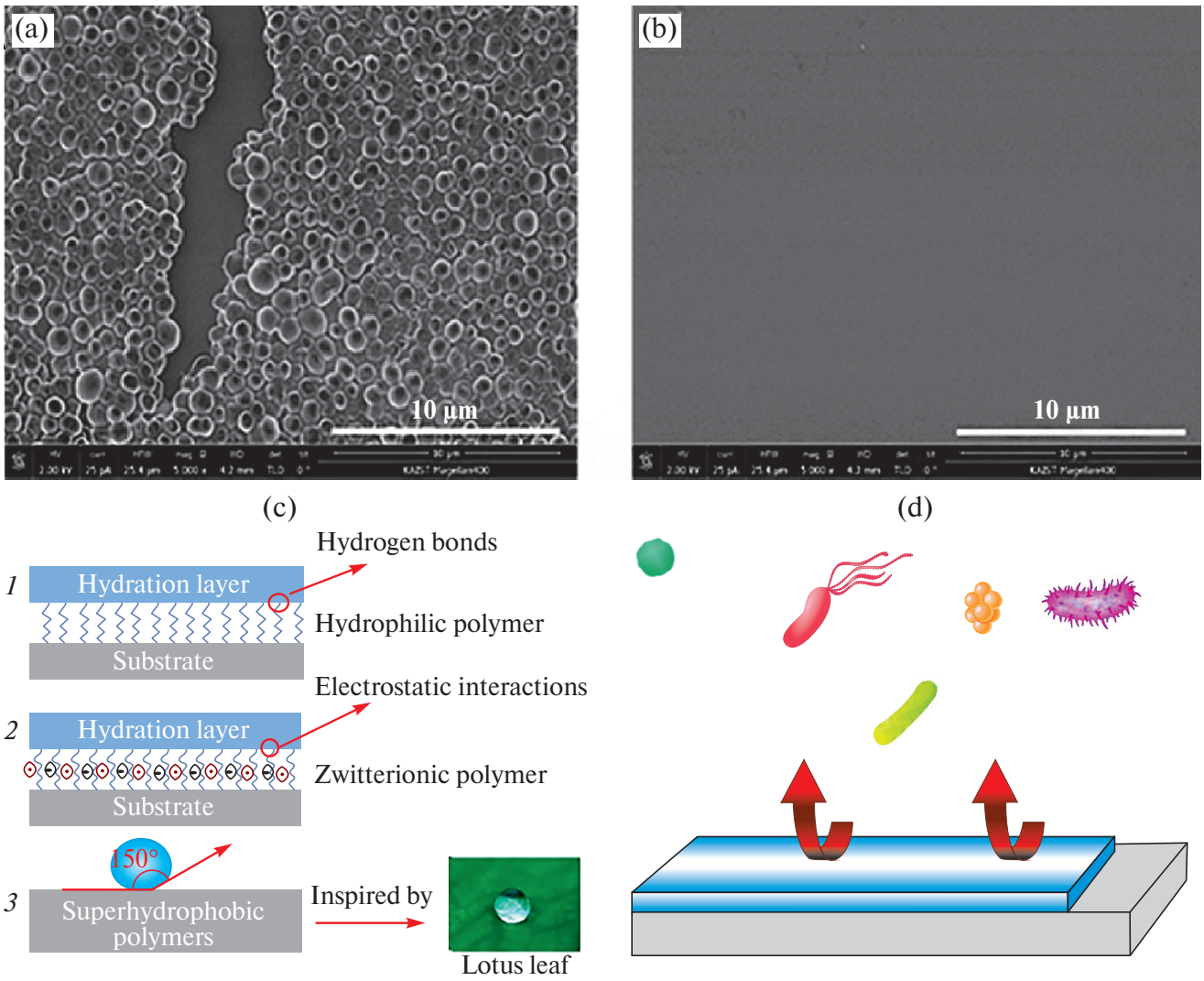

Fig. 3. a – Electron micrograph of a 7-day *S. aureus* biofilm on an uncoated surface; b – Electron micrograph of a polydodecyl methacrylate-polyethylene glycol methacrylate-acrylic acid coating preventing biofilm formation from *S. aureus* for 7 days. Reproduced from [43], with permission from the American Chemical Society, 2017; c – Schematic representations of anti-adhesion coatings. (*1*) Hydrophilic polymers, (*2*) zwitterionic coatings, (*3*) superhydrophobic coatings, water contact angle greater than 150° like in a lotus leaf. Reproduced from [93], with permission of John Wiley & Sons, Inc., 2020; d – Schematic representation of the mechanism of action of the anti-adhesion coating.

Multifunctional antimicrobial coatings

Advances in antibacterial and antifouling coatings have provided the basis for the development of multifunctional coatings [111–113]. They represent a class of antimicrobial materials that, in addition to inactivating bacteria, have additional capabilities such as long-term activity, stability, and recoverability. Various studies have shown that such coatings can reduce the number of bacteria on a surface by more than 99% compared to an uncoated surface [114–116]. The mechanism of action of multifunctional antibacterial coatings (Fig. 4a) includes: antibiofouling, bactericidal and removal of dead and/or live attached bacteria. Thus, the surface can resist or prevent the initial adhesion and spread of bacteria by steric and electrostatic repulsion or by reduced surface energy, and if bacteria make contact or partially attach to it, the bactericidal additives contained in the coatings destroy them (Fig. 4b, c) [117, 118]. Depending on the method used to incorporate antibacterial agents into anti-adhesion materials, such surfaces can be divided into three categories: bound to hydrophilic polymers, layer-by-layer applied or retained in and released from a non-fouling matrix. Natural and synthetic chemicals such as QASs compounds, antimicrobial enzymes, AMPs, chitosan and bacteriophages can be used as antibacterial agents [119]. Such coatings are prepared by sequential layer deposition, chemical modification, plasma deposition, covalent binding, conjugation, immobilization and graft polymerization [120].

Despite the high efficiency of multifunctional coatings, there are still many unsolved problems in the practice of their application and manufacture. Bactericidal agents included in the composition of such coatings have disadvantages related to storage stability, long-term effectiveness, biocompatibility, cost and labor intensity of their introduction into the coating composition. In addition, it is quite difficult to select materials for coating development that exhibit good biocidal activity, bacterial resistance properties and removal of dead bacteria. When using multifunctional coatings on medical devices, it is necessary to consider their composition, as it is not always the case that materials that combine antibacterial and anti-adhesive properties can be a universal means of combating bacterial infections. For example, the use of anti-adhesive materials is inadmissible in the manufacture of orthopedic and dental implants, because the surfaces must inhibit bacterial colonization and simultaneously promote osteoblast adhesion [121]. At the same time, the use of anti-adhesive materials in the fabrication of multifunctional coatings for urinary and intravascular catheters enhances the bactericidal properties of the surface because they do not require special conditions in addition to antibacterial properties [122]. Moreover, for practical applications, surface fabrication should be simple, inexpensive and reproducible. For objects in contact with seawater, it is essential that the surfaces demonstrate enhanced corrosion resistance and durability, as well as resistance to fouling by various organisms that may colonize any underwater surface [123]. It should be noted that for biomedical applications, the toxic effects of antibacterial surfaces need to be determined first and their biocompatibility improved [124].

Intelligent antimicrobial coatings

In recent years, smart antibacterial coatings have been developed that combine: anti-adhesion, bactericidal and self-cleaning functions, and realize controlled release

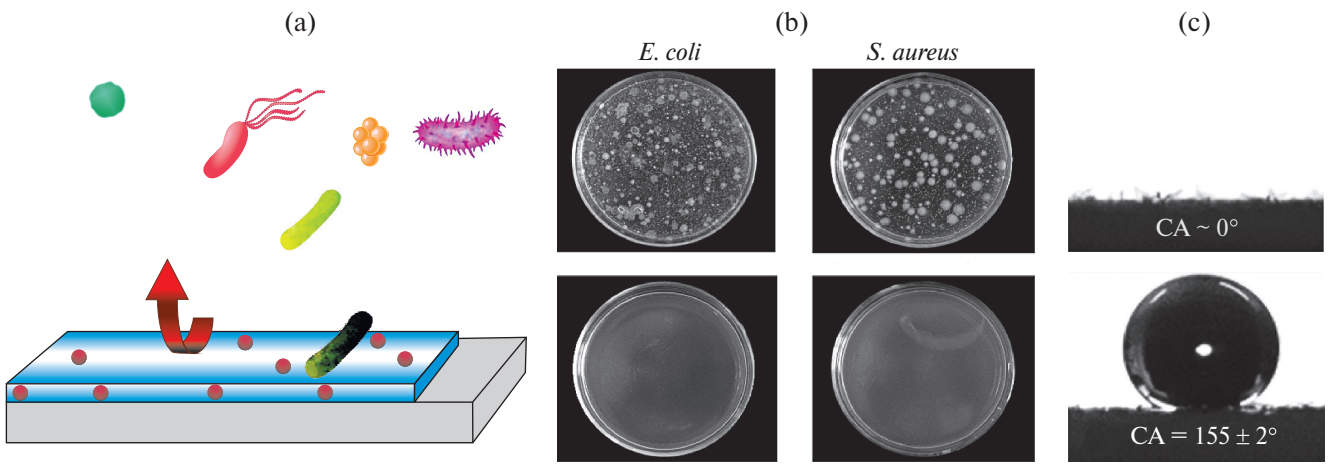

Fig. 4. a – Schematic representation of the mechanism of action of multifunctional antibacterial coating; b – Antibacterial activity of uncoated and coated cotton fabrics containing polyethylenimine, phytic acid, iron ion (Fe3+) and dimethyloctadecyl [3-trimethoxysilyl-propyl] ammonium chloride against *E. coli* and *S. aureus*, respectively; c – Optical images of water droplets placed on uncoated and coated cotton fabrics, respectively. *E. coli* and *S. aureus*, respectively; c – Optical images of water droplets placed on uncoated and multifunctional coated cotton fabrics, respectively. Reproduced from [48], with permission from Elsevier B.V., 2022.

of antibacterial agents through physical and chemical approaches, thereby achieving prolonged exposure, reducing potential side effects (Fig. 5a). Thus, smart antibacterial coatings are considered to be most optimal of all existing coatings. They can be categorized into endogenously and exogenously responsive types [125]. Endogenously responsive coatings primarily involve response to pH and bacterial secretions. The former is mainly stimulated through acidification of the medium by bacterial infection [126], whereas the latter refers to the response to various enzymes (such as phospholipase, hyaluronidase, cholesterol esterase and metalloprotease) or toxins secreted during the metabolic process [127, 128]. Conventional pH-sensitive coatings are produced by electrostatic interactions. For example, coatings containing negatively charged molecules and positively charged antibiotics are prepared by layer-by-layer self-assembly [129–132], or acid-sensitive Schiff bases [133, 134], metal coordination bonds [135], and boronic acid esters [136, 137] are used for synthesis. In addition, pH-sensitive coatings can be derived from reactive binding between nanoparticles and drugs, as well as sensitive molecules such as polymethacrylic acid [138]. Exogenously stimulated coatings exhibit antibacterial activity when stimulated by external conditions. Such coatings can solve the problems of poor stability, uncontrolled drug release and emergence of bacterial resistance. Exogenously sensitive coatings include temperature responsive surfaces,

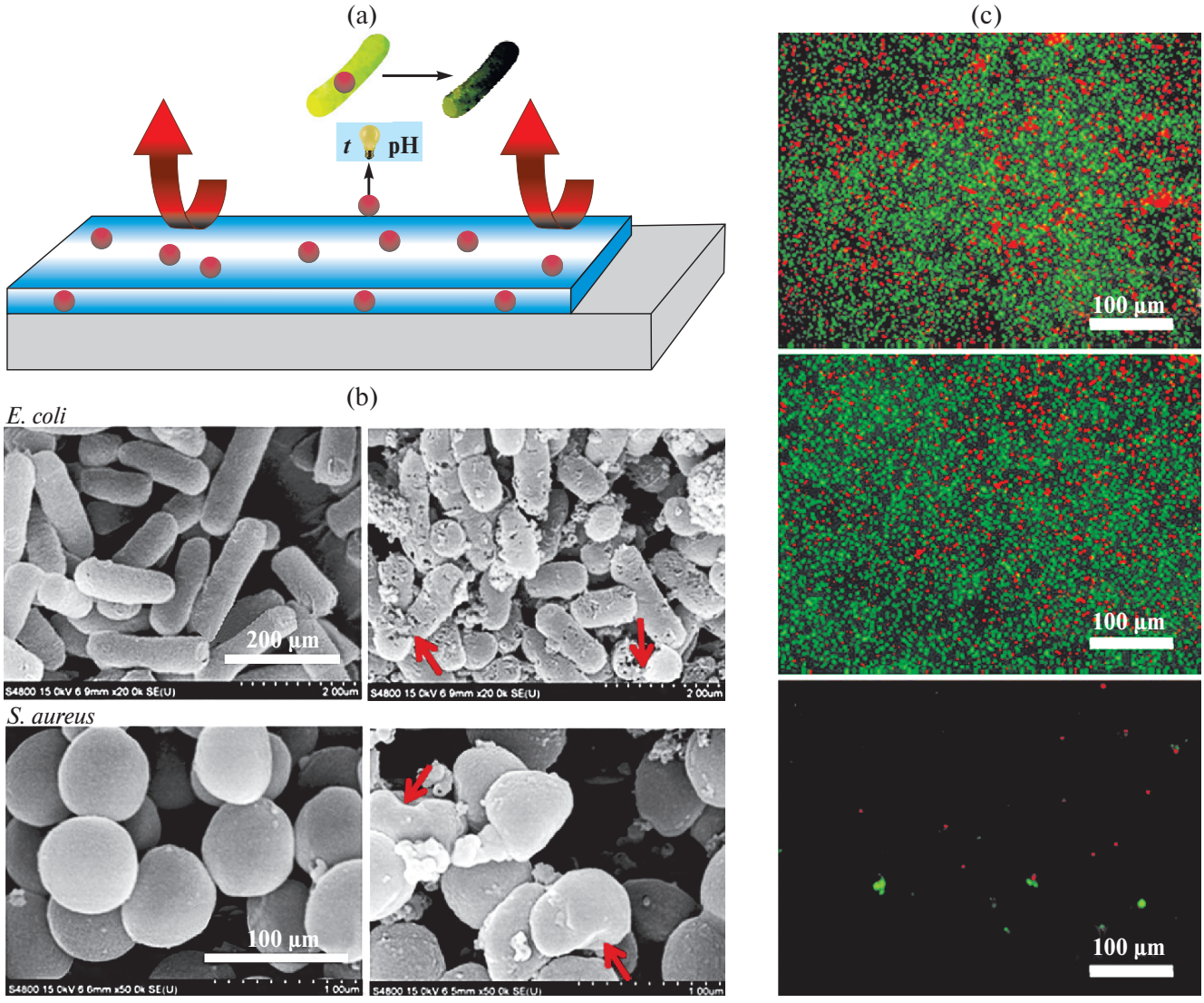

Fig. 5. a – Schematic representation of the mechanism of action of the smart antibacterial coating; b – Electron micrographs of *E. coli* and *S. aureus* cultured with carbon capsules modified with polyethylene glycol and doped with nitrogen with and without 808 nm laser irradiation. Reproduced from [138], with permission from the American Chemical Society, 2018; c – Confocal microscopy images of viable cells (green) and dead bacteria (red) of *S. aureus* obtained using confocal microscopy of uncoated 3D nanoporous surface, tannic acid-coated 3D nanoporous surface, tannic acid and gentamicin-coated 3D nanoporous surface, respectively. Reproduced from [129], with permission from the American Chemical Society, 2015.

photosensitive surfaces that are activated by light and bioelectric surfaces that are activated by an external electric field [139–141]. Such coatings are obtained by covalent bonding, vapor deposition, multilayer films or hydrogel coatings containing enzyme-sensitive components, photopolymerization, or a combination of several methods [127].

The analysis of the conducted studies indicates a great potential of smart antibacterial coatings for practical applications, but there is a lot of room for improvement of current coating methods to make them more effective, versatile and cost-effective. Promising in this direction would be the development of smart coatings that have the ability to activate biocidal activity in response to changes in certain biological microenvironments, as well as improving their stability, durability and reducing cytotoxicity [142].

CONCLUSION

In the last decades, active research has been conducted to improve antibacterial coatings and give them new properties such as the ability to regenerate and clean up dead bacteria. In addition, the combination of several antibacterial agents or the combination of different types of antibacterial coatings improve their effectiveness and durability. For example, in multifunctional materials where more than one protection strategy (superhydrophobic and anti-adhesive) incorporated into the coatings, bacterial adhesion is more effectively prevented, and if the compositions contain released antimicrobial agents, microbial cells will be inactivated upon contact with them. In addition, the need and use of an antimicrobial agent is reduced, and the service life of such a coating can be significantly longer than that of contact-type antimicrobial surfaces. Smart coatings based on the activation of antibacterial agents in response to changing environmental factors make surfaces even more effective durable, environmentally friendly, and in demand. Thus, further research on next-generation antibacterial coatings should focus on finding new and extending existing mechanisms of action against bacteria and developing additional pathways for their activation, as well as obtaining surfaces with multiple integrated functions.

The field of antimicrobial and antifouling surface development is a promising one and the potential for large and rapid impact through the implementation of developed technologies is evident. A large number of developments and studies described in the literature in the field of antimicrobial coatings do not reach practical application or even clinical trials. This is due to the fact that in laboratory conditions for testing antibacterial materials it is difficult to create conditions that occur in living organisms. The use of artificial intelligence and digital tools can help solve these problems. Thus analytical tools help to quickly and accurately process and analyze huge amounts of data, and artificial intelligence, by analyzing the chemical structure of coatings, helps to determine the toxicity of materials and select compounds for inclusion, saving time, resources and minimizing the risks of adverse effects in clinical trials.

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ETHICS DECLARATION

There are no human or animal studies in this paper.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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