Biotechnology and Bioprocess Engineering 23: 1-10 (2018)
DOI 10.1007/s12257-017-0348-0

pISSN 1226-8372
eISSN 1976-3816

REVIEW PAPER

Use of Nanoscale Materials for the Effective Prevention and Extermination of Bacterial Biofilms

Dohyun Lee, Youngmin Seo, Muhammad Saad Khan, Jangsun Hwang, Yeonho Jo, Jaewoo Son, Kyungwoo Lee, Chanhwi Park, Sachin Chavan, Assaf. A. Gilad, and Jonghoon Choi

Received: 5 September 2017 / Revised: 31 October 2017 / Accepted: 1 November 2017
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Abstract Biofilms have been shown to cause most human infections. The prevention and extermination of bacterial biofilms has always presented a major challenge in the clinic. The failure of traditional antibiotics and the development of bacterial resistance against these measures is on the rise. Nanoscale materials possess the advantage of presenting enhanced surface properties of bulk materials, and are emerging as effective agents for deterring microbial growth. This review article summarizes the fundamentals of bacterial growth, biofilm formation, mechanisms for antibacterial technologies, and usage of nanoparticles for the prevention and extermination of biofilms. Further research is required with respect to the appropriate usage of nanoparticles for the effective control of biofilms to save human lives and reduce healthcare costs.

Dohyun Lee†, Muhammad Saad Khan, Jangsun Hwang, Yeonho Jo, Jaewoo Son, Kyungwoo Lee, Chanhwi Park, Sachin Chavan, Jonghoon Choi*
School of Integrative Engineering, Chung-Ang University, Seoul 06974, Korea
Tel: +82-2-820-5258; Fax: +82-2-814-2651
E-mail: nanomed@cau.ac.kr

Youngmin Seo†
Center for Biomaterials, Biomedical Research Institute, Korea Institute of Science and Technology, Seoul 02792, Korea

Assaf. A. Gilad*
Russell H. Morgan Department of Radiology and Radiological Health, Johns Hopkins University School of Medicine, Baltimore MD 21231, USA
Cellular Imaging Section, Institute for Cell Engineering, Johns Hopkins University School of Medicine, Baltimore MD 21231, USA
Tel: +1-410-502-8188; Fax: +1-517-355-2288
E-mail: assaf.gilad@jhu.edu

†These authors contributed equally to this work.

Keywords: biofilm, nanomaterials, anti-bacterial property, nanotechnology

1. Introduction

Historically, microorganisms have been considered to be planktonic (freely swimming) cells, but recent studies have revealed that microorganisms tend to aggregate into complex multicellular structures, in which cells stick irreversibly to each other and to the surfaces [1,2]. These aggregated microorganisms are enclosed within a protective and self-produced extracellular matrix, that forms a film covering the surface and results in a structure known as a biofilm [3,4]. The term 'aggregated' describes the fact that most cells experience cell to cell contacts in multicellular structures, thus distinguishing themselves from free living microorganisms [5]. Biofilms have been found in the early fossil record, dating back to some three-billion-year-old fossils. Moreover, similar biofilm structures are common in hydrothermal environments, such as hot springs and deep sea vents [3]. The ability to form biofilms is common in prokaryotes (bacteria), and studies have revealed that a vast range of bacteria from gram-positive pathogens such as *Staphylococcus epidermis* to gram-negative bacteria, including *Pseudomonas aeruginosa* and *E. coli*, have this ability [6]. Biofilms may grow both on natural surfaces such as teeth, heart valves, and chronic wounds, and/or manmade surfaces, such as implanted medical devices, catheters and stunts, experimental setups, and industrial workplaces resulting in over 65% of all human microbial infections [2,7,8]. Airborne microorganisms can attach to wet surfaces and form biofilms, resulting in foul odors [9]. Owing to advances in molecular genetics and confocal microscopy, it has been

shown that the most common growth of microorganisms in nature occurs through biofilm formation [10]. Biofilm formation is highly undesirable because it increases the resistance of microorganisms to preventive and curative measures, and therefore, biofilms represent an increasing source of significant clinical and economical concerns [5,6].

A variety of antibiotics have been used to counter the hazards posed by biofilms. Nevertheless, resistance against antibiotics is increasing for the microorganisms inside of these biofilms, resulting in more severe and persistent infections [11]. Therefore, the mechanisms underlying microbial attachment and biofilm formation, and the investigation of antimicrobial measures are of great research significance for the efficient extermination and prevention of biofilm-related infections [12]. There is a constant need for developing new techniques, particularly for the elimination and prevention of biofilms.

Recent trends in nanotechnology focus on the discovery of more efficient and effective antimicrobial mechanisms, in the hope of implementing an effective prevention and extermination of bacterial biofilms. Implants such as artificial hip joints are tested for several basic characteristics such as biocompatibility, wear resistance, and stimulation of tissue integration. Aside from the use of multiple bactericidal coatings on these surfaces, new approaches, such as anti-adhesive nanopatterning, would allow the implant surfaces to possess antimicrobial functionalities. This would be useful in preventing biofilm development on the surface of implants [13]. The success of such nanotechnologies can minimize the dependence on traditional antibiotics, and consequently deter the development of antibiotic-resistant strains.

1.1. Bacterial biofilms

Bacteria are prokaryotes, with a diameter in the range of micrometers, containing structures and organelles that are protected by the cell wall and the cell membrane [14]. Bacteria exist in the form of either planktonic or sessile cells, and differ substantially in their structure, components, and functions. Research has unveiled that the ability to form biofilms represents an integral and ancient feature of bacteria, which ensures a favorable environment, mechanical protection, and high resistance against antibiotics [14]. Both gram-negative and gram-positive bacteria are known to form biofilms, which provide them with flexibility and resistance against antimicrobials [15]. Bacterial biofilms are commonly observed in moist areas, such as shower rooms, heat transferring units, as well as on the surfaces of implanted medical devices [9]. Bacteria can form biofilms in high shear stress environments, and these biofilms are stronger and more resistant to mechanical damage, when compared to bacterial biofilms formed in low-shear environments [16]. Moreover, the majority of infections which are hard to treat are caused by biofilms, including urinary tract infections, catheter infections, dental plaque formation [17]. Medical implants also present the risk of biofilm formation, resulting in serious infections on their surface following implantation, and such infections are very hard to treat, as they often require surgical intervention [3].

1.2. Biofilm structure

Biofilms are quite complex, as they are not homogenous monolayers of microbial cells, but structures composed of interacting heterogeneous microcolonies [16]. Biofilms generally consist of cells and a self-produced extracellular polymeric substance (EPS) matrix, which plays a key role in the integrity of microbes [2]. The formation of the EPS matrix is a dynamic process that depends on various factors including the presence of nutrients, shear stress, and the secretion and synthesis of extracellular material; this results in biofilm formation with high cell densities, in the range of 10^8 to 10^{11} cells/g wet weight [18]. The EPS matrix normally accounts for 50 ~ 90% of the total carbon mass of a biofilm, and provides structure and stability to the biofilm, while microbes only constitute 10 ~ 50% of the biofilm [2,18]. The EPS matrix usually varies in its chemical and physical composition, but it mainly contains polysaccharides, proteins, and DNA originating from the enclosed microbes [2,7]. The matrix is a heterogenous but highly ordered non-rigid structure that allows the movement of cells within the matrix, along with the exchange of nutrients, gases, and other molecules within the biofilms and with the outside environment [18]. The resultant biofilm structure is highly viscoelastic and behaves as a hydrogel, while its mechanical properties depend upon the environment [3,16].

1.3. Synthesis of biofilms

The life cycle is similar for most bacterial species, and

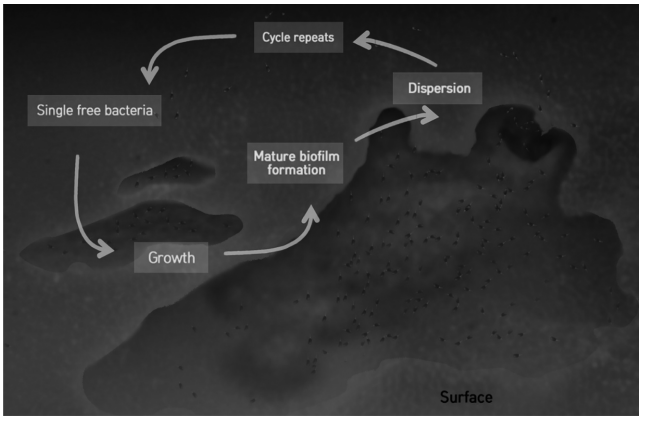


Fig. 1. The lifecycle of biofilm formation and growth.

includes the attachment of microbial cells, their growth and development, maturation, and dispersal. These stages in the formation of a biofilm are shown in Fig. 1, and are explained below.

1.3.1. Attachment

All microorganisms have the natural ability to attach to a surface, which is advantageous for their survival [8]. The attachment to a surface represents an initial event in the biofilm formation process on both biotic (natural) and abiotic (manmade) surfaces [5]. The initial attachment is affected by a variety of important factors, such as the properties of a surface including hydrophobicity and roughness, the flow velocity of the surface surrounding medium, aqueous characteristics such as pH, temperature, nutrient levels, or ionic strength, and the properties of the microbial cell surface [2,4]. Planktonic microbes arrive on and loosely attach onto the surface, in a reversible manner [3]. After surface attachment, microbial cells start to synthesize the biofilm through their proliferation, aggregation, and the recruitment of surrounding cells [15]. In the case of bacteria, several proteins are strategically produced during the attachment phase, for effective binding to the extracellular matrix of target host surfaces [15]. Most researchers have argued that nonpolar hydrophobic surfaces attract more microorganisms than polar hydrophilic surfaces [2].

1.3.2. Biofilm growth and development

Following successful attachment, microbes grow and colonize the surface, usually by producing polysaccharides, that anchor the microorganisms to the surface in irreversible manner [19]. Due to the ability of microbes to stick to the surface and to each other, under favorable environmental conditions and abundant nutrient supply, microbial growth often leads to biofilm formation. The biofilm grows heterogeneously in a three-dimensional environment. The thickness and mechanical properties of a biofilm depend upon environmental factors. Thus, a high shear stress environment results in the formation of more resilient biofilms [3].

1.3.3. Biofilm maturation

At this stage, a structure is in place on the surface that provides a protective microenvironment for the microorganisms, and protects against antimicrobial agents and immune defense mechanisms [19]. The biofilm allows microorganisms to grow relatively unhindered, under protection from external stress, and it is under these circumstances that microorganisms are highly resilient [20]. Confocal laser scanning microscopy has revealed that after maturation, biofilms consist of a dense arrangement of cells enclosed within the EPS matrix, that can take various shapes depending on the nutrient source [3].

1.3.4. Biofilm dispersion

Cells in the biofilm can detach and disperse. Due to their dispersal characteristics, biofilm infections are recurring and persistent. The detachment of cells from the biofilm can be caused by internal processes or external factors such as nutrient levels, quorum sensing, or flow effects in the surrounding fluid [2]. Detachment or dispersal can occur either through single microbial cells, or through cell aggregates leaving the biofilm together [3].

1.4. The mechanism of biofilm resistance

Resistance represents the characteristic of microorganisms that enables them to survive in the presence of elevated levels of antimicrobial agents. Biofilms are known for their resistance against antimicrobial agents, as they are not easily eradicated by these agents [17]. A variety of bacteria have been reported to present a multifold decrease in susceptibility to antimicrobial therapies, when compared to planktonic free-floating microbes [4,6,21]. As suggested by these findings, the increased resistance of biofilms is caused by various factors such as the presence of a physical barrier in the form of the EPS matrix, the microbial cell density in the biofilm, slower growth rates, differences in gene expression patterns, and the role of efflux pumps in the cell membrane [4,6,11].

1.4.1. Restricted penetration due to the EPS matrix

The EPS matrix provides a physical barrier through its complex matrix architecture, that prevents traditional antimicrobial agents from efficiently reaching their target microorganisms [4]. The EPS matrix effectively dilutes charged, reactive, or large antimicrobial agents before they can reach individual cells within the biofilm. The EPS matrix barrier might also protect against UV and dehydration [3].

1.4.2. Slow growth rate

Fast-growing microorganisms are more susceptible to antimicrobial agents. Bacteria with faster metabolic rates are easily targeted by antibacterial agents, while slow growth rates improve bacterial resistance [22]. Due to the altered microenvironment, biofilms maintain a slow growth rate, which enhances microbial resistance against antimicrobial agents [20,23,24]. Starved, stationary-phase dormant zones in biofilms, that show the least biological activity, are also resistant to most antibiotics [3]. Moreover, enzymes that are involved in protecting bacteria against stress are more abundant in slow-growing, less active microorganisms. For example, starvation can initiate a survival state in bacteria, decreasing the rate of gene replication. Due to this stress response mechanism, slowly replicating bacteria are more resistant to antibacterial agents [20,25].

1.4.3. Expression of specific genes

Microorganisms in biofilms differ phenotypically from planktonic microorganisms. Due to the biofilm environment, a large set of genes are regulated and optimized to adjust to these new conditions. Studies have shown that biofilm formation involves several signaling pathways and a genetic program that enables the transition from a planktonic growth state to a biofilm growth state. For example, the transcription of the *algC* gene, which is involved in the production of alginate, increases four times in *P. aeruginosa* biofilms; in addition, *alg*D, *rpo*S, *alg*U, and genes that show correlation with polyphosphokinase synthesis are known to be upregulated during the formation of biofilms [16,26]. Similarly, the *S. aureus* can secrete a large range of substances including fibronectin-binding proteins FnBPA and FnBPB, collagen-binding Cna, and clumping factors ClfA and ClfB, for effective binding on surfaces [15].

1.5. Limitations of traditional antimicrobial drugs against biofilms

The antimicrobial activity of a compound consists in the killing or decreasing the growth of microorganisms, without being toxic to the surrounding tissues [22]. Given their broad usage, microbial resistance to antimicrobial agents is becoming very common. Methicillin resistance is well known, and represents a critical issue in the clinic. During 2005, approximately 94,360 cases of methicillin-resistant *Staphylococcus aureus* (MRSA) infections occurred in the United States alone, 18,650 of which were fatal [15]. Another prominent example is multidrug-resistant tuberculosis (MDR-TB), which is resistant to previously effective antibiotics [22].

As described earlier in detail, biofilms provide a specific microenvironment for microbes, which is needed for their high resistance against antimicrobial agents [20,23-25,27]. Antibacterial mechanisms typically degrade the cell wall, infiltrating this protective barrier and reaching the susceptible cellular inner components, while biofilms provide protection to the microbes inside this structure. A variety of antibiotics have been employed to counter bacterial hazards in biofilms, but the resistance against such measures is usually high, resulting in resistant bacterial strains and persistent infections [11]. It has been reported that bacteria in biofilms are 1000 times more resistant to antibiotics compared to their planktonic counterparts [28]. The resilience of bacteria often results in biofilm recovery and reformation, rendering traditional antibiotic measures obsolete. Hospital acquired infections are on the rise, and approximately 70% of these bacterial infections are resistant to at least one commonly used antibiotic [29].

Since the EPS matrix of the biofilm is a heterogenous structure, it is difficult to determine the optimal minimum inhibitory concentration (MIC) for the antimicrobial agents contained within. The growth parameters of a biofilm, such as the surface area to volume ratio, the residence time of the fluid in the biofilm, or the nutrient loading rate, remain uncharacterized [3]. It is therefore a recognizable fact that biofilm prevention and elimination requires serious attention, because the consequences of antimicrobial resistance are higher mortality rates and increased healthcare costs [29].

2. Anti-microbial Nanoparticles

Bio-materials have been used in numerous antimicrobial applications, including the treatment of inflammation and burns, drug delivery, and biochips. Studies concerning the

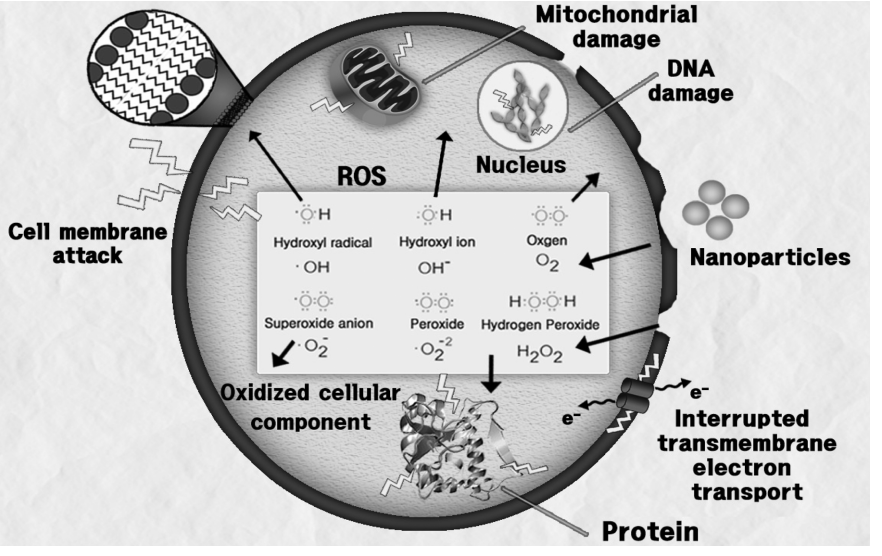


Fig. 2. Reactive oxygen species (ROS) generated inside the mammalian cell by antimicrobial nanoparticles.

effects of these materials have consequently led to a decreased particle size and an increased surface area, resulting in modern nanoscale particles [9]. Nanoscale-sized materials are more effective as antimicrobial agents when compared to their bulk equivalent, because at least 50% of these particles are present at the surface and can react with the microorganism, thus enhancing the surface area and increasing reactivity [14]. This high surface to volume ratio alters the physical, chemical, mechanical, and optical properties of nanoparticles, among others, making them significantly different from their bulk counterparts [22]. Upon contacting the microorganism, nanoparticles may puncture its cell wall, alter cellular permeability and lyse the plasma membrane [30].

As shown in Fig. 2, nanoparticles may perform anti-microbial actions using several mechanisms such as : (1) binding to the cell wall to penetrate the structural boundaries and form holes or pits on the surface, changing cell permeability, and compromising cellular components and their functions; (2) anchoring onto the membrane and creating a polymer membrane layer on the surface, thus preventing cellular intake and secretion; (3) inducing oxidative stress by generating Reactive Oxygen Species (ROS); (4) releasing ions that bind to the cell membrane and interact with intracellular thiol groups; (5) damaging DNA *via* acid-base reactions, ultimately disrupting the ability of the bacteria to replicate [9,12,14,15,31-39].

Antimicrobial mechanisms employed by nanoparticles, particularly in biofilms, need to be further explored, to develop a more in-depth understanding of the processes involved. Nanoparticles have the capability of compromising the structural integrity of bacterial cellular components, and may interfere with the electrochemical interactions of surfaces or enzymes that play a crucial role in bacterial survival. The mechanisms employed by nanoparticles depend upon the particle type, bacterial species, and size, as well as external environmental factors such as pH, temperature, or contact surface, which may have a considerable impact on test results [9,12,14,15,31-39].

2.1. Common antimicrobial non-oxidized metals

Silver is widely known for its antimicrobial properties and has been used for treating wounds, burns, and bacterial infections [37]. Although the use of antibiotics has decreased the use of bulk silver, nanotechnology has brought this material back into usage, with new physiochemical and optical properties to explore. As a nanoparticle, silver has made fast progress in terms of performance as an anti-microbial agent, and is still a promising candidate for diverse applications in biomedical studies [30,33,38,40]. Silver nanoparticles have been reported to have anti-biofilm properties by inhibiting the ability of microorganism to synthesize EPS, and thus effectively inhibiting biofilm formation [41]. The antimicrobial action of Ag^+ is particularly efficient against gram-negative bacteria, inhibiting cell respiration when Cl^- precipitates as AgCl in the cytoplasm [14]. In addition to interfering with cell respiration, it is also known that Ag^+ may damage DNA *via* acidic/basic interactions, inhibiting replication [33,36,39,42,43].

Gold nanoparticles have been reported to exhibit high anti-bacterial activity, especially against gram negative bacterial species, depending on the size and dosage of the nanoparticles [44]. In addition to its singular use, Au has been experimented with other materials such as Ag, owing to its great malleability and versatility. A multi-layered core/shell structure of the two metals has been revealed to show synergistic antimicrobial effects that vary with shell thickness [45]. In addition, several other materials such as Pb, Co, and Ni may also be used to decorate carbon nanostructures for the inhibition and extermination of biofilms [43].

2.2. Common antimicrobial oxidized metals

Zinc oxide is well known for its antimicrobial effects that occur through several proposed mechanisms, such as the induction of oxidative stress, membrane disorganization, and the release of Zn ions, which changes the bacterial microenvironment [46,47]. Titanium oxide, TiO_2, is known for its non-toxic and self-disinfecting properties, and has been used in drugs, cosmetics, food, and materials. TiO_2 is also effective against a large variety of bacteria, and is mainly used for the disinfection of drinking water and in food packaging [48]. The antimicrobial activity of TiO_2 is strongest when photocatalytic ROS production is activated upon illumination. Nevertheless, bacterial cell death has also been observed in the dark while using TiO_2, but it was less pronounced, suggesting that other unknown mechanisms might also be involved [48]. Other commonly used oxidized metals include CuO, Al_2O_3, Fe_2O_3, or SiO_2, along with the rare earth metal Y_2O_3 [48,49]. These particles present the advantage of increased binding properties to the cellular walls of bacteria and strong ROS generation, thus the frequent usage with other antimicrobial composite substrates, or directly on the bacterial cell walls. Al_2O_3, SiO_2 and ZnO have been reported to display higher toxicity when used as nanomaterials, as compared to their bulk counterparts [50]. Table 1 summarizes various nanoparticles and their use as antimicrobial agents against specific bacterial species.

3. Nanocomposites

Nanocomposites are composed of two or more nanoparticles having antimicrobial properties that are evenly dispersed on the chosen substrates, according to the required applications.

Table 1. Common examples of nanoparticles and their antibacterial action

Material	Size	Applied dosage	Bacteria	Notes	Reference
ZnO	<100 nm	2 ~ 5 mM	*(Halophilic) Bacterium sp. EMB4*	Causes membrane disruption and ROS inhibition	[22], [66]
	<100 nm	10 nM	*B. subtilis*		[22], [66]
	18 ~ 22 nm	10 ~ 100 μg/mL	*E. coli* *P. aeruginosa* *B. subtilis* *S. aureus*		[49]
	<20 nm	20 mg/L	*E. coli*		[22], [50]
	25 ~ 40 nm	8 and 80 ng/mL	*Sal. typhimurium*		[22], [67]
Ag	<100 nm	10 nM	*B. subtilis*	Binds to amines and carboxyl groups. Possesses strong antimicrobial properties, may be less effective against gram-positive bacteria	[22], [66]
	1 ~ 10 nm	25 ~ 100 mg/L	*E. coli*		[22], [68]
	~10 nm	1 mg/L	*P. putida KT2442*		[22], [69]
	21 nm	75 μg/mL (All types 100% reduced)	*E. coli* *V. cholera* *S. typhi* *P. aeruginosa*		[12], [68]
CuO	8 ~ 10 nm	Not determined	*B. subtilis*	Binds to amines and carboxyl groups	[22], [70]
	25 ~ 40 nm	1 mg/L	*P. putida KT2442*		[22], [69]
	27 ~ 31 nm	10 ~ 100 μg/mL	*B. subtilis* *S. aureus* *E. coli* *P. aeruginosa*		[49]
TiO_2	40 ~ 60 nm	N/A	*B. subtilis*	Needs photoactivation	[22], [50]
	10 ~ 25 nm	10 mg/L	*P. aeruginosa*		[22], [71]
	~ 50 nm	20 mg/L	*E. coli*		[22], [50]
	20 nm	10 mg/L	*E. coli*		[22], [50]
	40 ~ 60 nm	8 ~ 80 ng/mL	*Sal. typhimurium*		[22], [67]
SiO_2	20 nm	Not determined	*E. coli* *B. subtilis* *P. fluorescens*	Flocculation, membrane disruption	[12], [50]
Al_2O_3	11 nm	10 ~ 500 μg/mL	*E. coli*	Dose-dependent ROS, particle penetration	[12], [72]
	60 nm	20 μg/mL	*E. coli* *B. subtilis* *P. fluorescens*	Flocculation	[12], [22], [50]
Fe_2O_3	33 ~ 37 nm	10 ~ 100 μg/mL	*B. subtilis* *S. aureus* *E. coli* *P. aeruginosa*	Stronger against *B. subtilis* than others	[49]
Au	7 ~ 34 nm	5 ~ 30 μL	*S. aureus* *E. Coli*	Optical properties	[44]
Y2O3	23 ~ 64 nm	10 ~ 100 μg/mL	*E. coli* *P. aeruginosa* *S. marcescens* *S. aureus*	Derived from extract of *A. indica* leaf	[73]

Nanoparticles may have satisfactory properties when it comes to simple applications, but critical disadvantages may sometimes accompany raw usage. Singular nanoparticles possess elevated levels of surface energy, making them highly reactive and prone to aggregation, thereby rendering them lower in efficiency than theoretically anticipated. In an attempt to overcome this phenomenon, nanocomposites have been studied for practical use [51].

3.1. Natural polymer nanocomposites (antimicrobial metal-decorated natural polymers)

Chitosan is a commonly used natural polymer in nano-

composites. It is derived from chitin, one of the most abundant polysaccharides in nature, and structurally resembles glycosaminoglycans, which are found in the animal extracellular matrix. Chitosan possesses key biodegradable, biocompatible, and antimicrobial properties that are essential for antimicrobial activity [52,53]. The exact antimicrobial mechanisms underlying the action of chitosan remain yet to be clarified, but several studies point towards two potential theories, mostly related to the adhesion of chitosan to negatively charged surfaces: one being that chitosan enters the cell wall through pervasion, that prevents/disturbs the physiological activity of the bacterium, while the other involves the formation of a polymer membrane on the surface, that prevents nutrients from entering the cell [53,54]. The combination of chitosan and silver in nanocomposites results in improved tensile strength and antimicrobial properties [53]. Other studies have shown that a combination of chitosan and titanium oxide yields promising results, and may promote wound healing. Overall, greater antimicrobial benefits were found when mixing chitosan, TiO_2, and Ag at a certain concentration (0.005; 0.003 wt.%), when compared to chitosan without nanoparticles [35]. Chitosan, TiO_2, and Ag, in combination, elevated oxidative stress and membrane permeability (LDH), when compared to the control, and emphasized the need for an in-depth exploration concerning the numerous possibilities for using chitosan/TiO_2/Ag nanocomposite films in antimicrobial applications [35].

3.2. Carbon structure nanocomposites (antimicrobial metal-decorated carbon nanostructures)

Graphene oxide and carbon nanotubes (CNTs) are useful for applications that require the use of a substrate with a large surface area, mechanical strength, and electroconductivity. Several studies have demonstrated that CNTs decorated with nanoparticles such as Ag, Fe, Pt, and Cu display strong antibacterial activities [9,51,55-57]. Solar irradiation has also been studied as a means to enhance the synergistic effects of these nanocomposites [51]. The antimicrobial performance of these composites depends upon the type of nanoparticle, size distribution, and even dispersion of the particles along the surface of the carbon structures, which makes the synthesis of such structures more challenging [9]. Various types of covalent and non-covalent surface modifications are also being explored and developed, including electrochemical treatment, polymer wrapping, and plasma treatment to enhance the antimicrobial properties of carbon nanostructures [51]. Moreover, other studies have investigated the use of carbon nanostructures with functional groups such as thiols, amines, or carboxylic acids attached on their surface, which aided in the conjugation of nanoparticles of interest [9].

Other notable nanocomposites may consist of metals alone, such as Ag-TiO_2 or MgO-Ge in powder form, or may be combined with other materials such as cellulose or zeolite [21,58-60].

4. Preventive Antimicrobial Nanotechnology

The prevention of biofilm formation represents a key factor especially for medical implants, surgical tools, and other applications. Nanoparticles can also be used as a preventative tool to inhibit the formation of biofilms on these surfaces. Two major applications of antimicrobial technology, nanopaints and nanotextiles, are abundant in modern society.

4.1. Nanopaints

Paints have been used for decoration and protection, and are still in use for various purposes. Paint quality and performance is increasing due to the remarkable advancements in the field of polymer chemistry. Dispersion kinetics have brought about countless opportunities for quality and function, and nowadays, there are numerous types of paints that are used for industrial purposes such as scratch resistance, hardening, and glossiness, as well as for antimicrobial applications, self-cleaning, and antifouling [61]. Nanoclays or nanoscale ceramic particles may be utilized in various polymers that incorporate heat-induced cross-linking mechanisms, thus boosting paint hardness for use on automobiles [62,63]. In some cases, paints may be based on nanocomposites, where the nanoparticles in the paint are homogeneously mixed, to utilize the advantages of both their organic and inorganic natures: hardening and breathability, as well as elasticity and hydrophobicity [62]. Other paints that include self-cleaning or antimicrobial features are abundantly being used for homes and other living environments. These paints allow foreign substances to be easily washed away, or prohibit microbial attachment, and are usually based upon photocatalytic and hydrophobic principles—an example being titanium oxide nanoparticle-related products [62,64].

4.2. Nanotextiles

The term nanotextiles encompasses a large scope of materials made of pliable fibers that are intertwined or bonded by chemical or physical processes, in nanoscale. Textiles are being used in garments and everyday utilities, as well as for architectural and landscape applications. Some textiles will require strength; other applicable features include fire resistance, optical, photovoltaic, and thermal characteristics, as well as utilization in the technological fields of biofilters, absorbents, and biosensors [62]. Nanoscale surface modifications may also be made upon these textiles for self-cleaning, antimicrobial, anti-staining, and filtering features

[65]. For instance, palladium and silver nanoparticles have been used for their antimicrobial properties in fashion design, in the form of dresses, jackets, and leggings [62]. Anti-staining applications require engineering techniques that manipulate the principles of light or color. Most of these textiles are constructed with composite fibers by incorporating various nanostructures with certain polymeric matrices, resulting in enhanced molecular functionalities [63]. Also, nanoporous layers have been used in fabrics that display hydrophobic self-cleaning mechanisms, as well as in photocatalytic coatings with anti-staining properties, considered to be adequate for public areas and households [62]. Besides the surface modification of materials involved in lasting direct contact, biofilters, such as air and water purification devices, may be coated with nanoparticles as an example of modifications in indirect contact materials.

5. Conclusion

Antibiotics are faced with increased resistance, and the deposition of biofilms onto various surfaces is becoming more hazardous, as the bacteria are becoming more resistant towards traditional antibiotics. Therefore, new mechanisms are required for the prevention and extermination of biofilms. The usage of nanoparticles and nanotechnology to counter microorganisms has increased considerably due to a better understanding of their interactions and mechanisms. However, several challenges still exist for the safe and reliable use of these particles in antimicrobial applications. A complete analysis of the genes and enzymes that participate in cellular signaling during ROS elevation still demands more study, in addition to the signaling mechanisms, biofilm prevention, or any unknown adverse effects of nanoparticles on cells. There are still health issues to address, regarding the risk of nanoparticle inhalation or ingestion, while their accumulation in blood vessels may also represent a potential cause for concern. Moreover, the further commercialization of antimicrobially coated surfaces for use in applications requiring critical hygiene should be met in the imminent future, possibly by adopting physical prevention methods, such as nanoscale 3D printing.

Acknowledgements

This study was supported by Chung-Ang University Research Grants (2016) and also by Nano•Material Technology Development Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science and ICT(No. 2017M3A7B8061942).

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