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Properties, mechanism and applications of diamond as an antibacterial material

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ABSTRACT

Antibiotic resistance in bacteria is a current threat causing an increasing number of infections of difficult clinical management. While the overuse and misuse of antibiotics are investigated to reduce them, the need for alternatives to approaches is rising. Carbon-based materials shown recent moderate to high antibacterial properties and diamond, thanks to its superior mechanical, tribological, electrical, chemical and biological quality is a choice material to investigate for safe antibacterial films, coatings and particles. Here, the antibacterial properties of diamond films, nanodiamonds, DLC films and a comprehensive list of the composites developed from them are discussed along with a summary of the bacterial strains used and the most efficient composition and/or concentration discovered. In a later stage, the mechanisms of action and the parameters that are believed to influence them are discussed and finally, an overview of the biomedical and food industry applications is given.

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1. Introduction

Antibiotic bacterial resistance is a challenge of this century posing health problems [1] that are spreading fast at different scales: Humans bearing antibiotic-resistant bacteria [2], dissemination of antibiotics and antibiotic resistance genes in the environment [3–5]. The decreasing antibiotic efficiency gives the space for the development of bacterial infections and contamination that are a lot less treatable as they used to be. It emerged because of the over- and misuse of antibiotics in human healthcare [6–9] and the lack of proper removal from hospital wastewaters [10], as well as livestock since their antibacterial properties are combined with a growth factor promotion effect [11]. It was a strategy to use them as preventive in the food industry to increase the quantity of meat and dairy products to feed the always growing and demanding population while keeping safe-to-consumption products [12–17]. However, research is already focusing on how to reduce the over- and misuse of antibiotics in these contexts [18–22] which aim to prevent the emergence of new resistances effectively in the future. Nonetheless, the resistances that already appeared and spread need to be assessed and treated with alternative medicine and to be kept under control by efficient antibacterial surfaces and coatings.

Metal-based antibacterial materials were among the first investigated and showed high antibacterial properties, often able to kill resistant bacteria [23–30]. However, rising concerns about their cytotoxicity against mammalian cells oriented the research to more biocompatible materials such as carbon-based materials. With several of them showing interesting antibacterial properties such as graphite [31–34], graphene [35–38], and carbon nanotubes [39–43] to cite only a few of the latest references, carbon-based materials are definitely an interesting strategy to explore to keep surfaces bacteria-free or to reduce infection based on Antibiotic-Resistant Bacteria (Table 1).

Thanks to its superior hardness, resistance [179] and tribological properties [180–187], fluorescence outside of the biological range [188, 189], electric and electronic properties [190–202] (noticeably as a substrate for Metal Oxide Semiconductor Field-Effect Transistor [203]), easy surface functionalisation [198, 204] and chemical inertness [205], the diamond appeared, despite its price, as a choice base material for the development of antibacterial coatings, films and particles. In this review, the antibacterial properties of diamond films, diamond nanoparticles, and the main composites developed from them are investigated as exhaustively as possible. On a later stage, the antibacterial mechanisms of action of diamond-based antibacterial materials are discussed, as well as the important parameters reported by the literature explored. Finally, an overview

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of the targeted applications for such antibacterial coatings and particles is built, focusing mainly on the biomedical applications and the food industry, two of the most important fields where antibacterial materials are needed nowadays.

1.1. Diamond materials with antibacterial properties

1.1.1. Antibacterial diamond films

Diamond films are of interest as a surface coating or for the strengthening of existing materials. In the applications where antibacterial properties are an additional need to strength, electric conductivity, biocompatibility, or chemical inertness, they were investigated for their performances. Different parameters were studied: different bacterial cultivation media [206], different surface structures [158, 206, 207], different textures [208], different bacterial strains such as *Pseudomonas aeruginosa* [207, 208], *Escherichia coli* [158, 206, 209], and *Bacillus subtilis* [210], different surface and in-depth functionalisation [158, 206, 209, 210] and the mechanisms of action were explored.

Through their investigations on the culture media used for the bacterial growth, Budil *et al.* show that the organic content of the culture medium was of importance in the adhesive properties and biofilm formation of *E. coli* on variously surface functionalised Nanocrystalline Diamond (NCD) films. The bacterial adhesion was reduced by about 50% when they used a mineral medium (M9) for NCD films functionalised with –H or –F. A complex organic medium, like the Luria-Bertani cultivation media, contains many organic compounds that are probably responsible of the passivation of the –H and –F termination, explaining why they were not efficient to reduce the bacterial adhesion. In other terms, such termination would be efficient to avoid bacterial biofilm formation and bacterial adhesion in a mineral environment or an environment containing a low amount of organic compounds able to interact with –H or –F terminations (Figure 1). Furthermore, Budil et al. also demonstrated that the substrate on which the NCD films are deposited does not

Table 1. Comparison of the mechanism of action, the cytotoxicity and existing bacterial resistance of common antibacterial materials.

Material categorie	Material	Mechanism of action	Cytotoxicity	Bacterial resistance?	References
Metal-based nanoparticles	Gold	Diffusion of cations, bacterial membrane disturbance, penetration into bacterial cells and metabolism disturbances	Medium	No	[44–54]
	Silver		High	Yes	[45, 46, 55–103]
	Copper		High	Yes	[59, 77, 81, 99, 104–121]
Carbon-based nanoparticles	Multi-walled and single-walled Carbon Nanotubes	Membrane puncture, cellular uptake and metabolism disturbance *via* ROS	Medium to Low	No	[77, 102, 122–137]
	Graphite	Mechanism not elucidated yet	Low	No	[31, 33, 34, 138–140]
	Graphene	Bacterial cell wrapping, membrane cutting	High	No	[49, 70, 75, 80, 102, 122, 141–153]
	Diamond	Membrane disturbance, cellular uptake, oxidative stress	Very Low	No	[154–178]

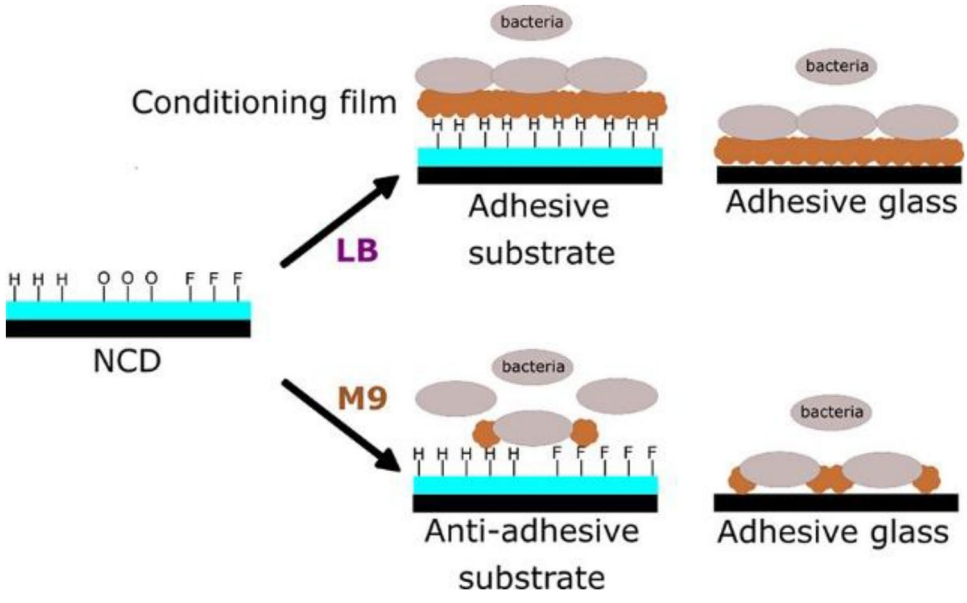

Figure 1. Influence of the culture media and surface termination on the bacterial adhesion onto UNCD films. Reproduced from [206] with permission.

influence the NCD films' performance. The study stresses the importance of the environment where the antibacterial/antibiofilm films based on diamonds are to be used as well as the atomic diamond termination [206].

As it was demonstrated with other materials investigated for their antibacterial properties, the surface structure of diamond films is a strategy to implement a mechanical antibacterial mechanism of action against certain strains of bacteria [211–215]. The motile bacteria, able to move by themselves in their environment such as *E. coli* are especially sensitive to sharp points able to puncture their membranes. The movements they will subsequently have to explore their environments for nutriments exploration can increase the puncture and lead to the internal cell content leakage, leading eventually to their deaths. An interesting structure proven efficient by different studies focusing on other materials was reproduced using a black diamond (bD) coating on silicon nanoneedles of about 5 µm length [158, 207]. The bD coating deposited and functionalised with different terminations (–H, –O, $–NH_2$ or –F) were able to combine the physical antibacterial mechanism of action of the nanoneedles to the chemical antibacterial mechanism of action. Surprisingly, despite changing the hydrophilicity of the nanoneedles film strongly, the different surface functionalisation didn't show significant differences in between them. They all show an increased chemical antibacterial rate of about 20–30% compared to the unfunctionalized bD nanoneedles [158]. This can be explained using the results of Burdil et al. described in the previous paragraph. *E. coli* was cultivated in Tryptic Soy Broth which is a culture media containing a high proportion of organic molecules able to passivate the surface termination of the nanoneedles. The increased chemical killing rate observed for all surface terminated nanoneedles could be attributed to the interaction between the organic molecules contained in the culture media and the nanoneedles, decreasing the number of organic molecules available for the bacterial growth [206]. In other words, it could be attributed to a reduction of the availability of the food for the bacteria in their environment because the food is trapped on the surface of the nanoneedles and they cannot use it for themselves.

Different bacterial strains were used in these studies. Two of them are Gram-negative: *P. aeruginosa,* and *E. coli.* All cited studies focusing on diamond films in these paragraphs are focusing on these two motile strains, and only one study cited here is focusing on Gram-positive bacteria, *B. subtilis* and compares results with a Gram-negative strain [210]. Merker et al. investigated the antibacterial properties of a composite film composed of silver nanodroplets capped with Ultrananocrystalline diamond (UNCD). Their results show that the actual antibacterial property of this composite is mainly dependent on the ability of silver to be released in the environment. The UNCD capping, here, acted more like a brake on the antibacterial properties than like a supportive layer. It is interesting to consider this capping technic to increase the time of silver diffusion in the environment and obtain a sustainable antibacterial diamond film [210]. However, their UNCD film, unlike the NCD film developed by Medina et al. [208], was not able to show intrinsic antibacterial properties. It confirms the high importance of the grain size control for the development of an antibacterial diamond film. Moreover, considering the large difference of bacterial membrane structure between Gram-positive and Gram-negative bacteria, more investigations on the Gram-positive strains are needed, especially on diamond films already demonstrating antibacterial properties against Gram-negative bacteria.

1.1.2. Antibacterial diamond particles

The antibacterial properties of diamond based materials are not only investigated as coatings or films but also as particles, often nanosized. They can be dispersed in biological media [175, 216] with specific surface functionalisation [173, 175] or to transport specific molecules [216] or added at the surface of a film or a coating to increase its antibacterial property [31, 217].

As a film or coating addition, nanodiamonds are interesting for different properties. Firstly, they can increase the hardness of the material, increasing its range of application to environments with harder stresses. We effectively demonstrated in 2020 that the appearance of diamond microspheres with a diameter comprised between 10 and 30 µm on top of a graphitic coating could increase by a factor of 7 the Vicker's hardness of this coating without compromising their antibacterial properties against both Gram-positive and Gram-negative bacteria if in a moderate number [31] (Figure 2). But they are also useful to increase the antibacterial properties themselves because of their ability to interact with the bacterial cell walls. Guttiérrez et al. compared the antibacterial properties of a DLC film and a DLC film doped with Detonation Nanodiamonds (DND) against *E. coli*. After 6 h of interaction, the DLC DND film was able to reduce the bacterial growth of 95% which is very near the efficiency of their positive control, the streptomycin antibiotic. During the same contact time, the DLC film without DND doping was only able to reach 30% of bacterial growth inhibition, proving that the important bacterial killing effect of DLC DND film is mainly obtained thanks to the nanodiamonds (ND) present in the film. These antibacterial properties are attributed to the ability of the ND to interact with the bacterial cell wall, penetrate the cell, damage its genetic content and cause important oxidative stress, leading to the bacterial death. However, this very good antibacterial effect is time-limited. After 18 h of contact, the bacterial growth inhibition with the DLC DND film dropped to 20% while it maintained for the DLC film. The authors observed that the NDs at the

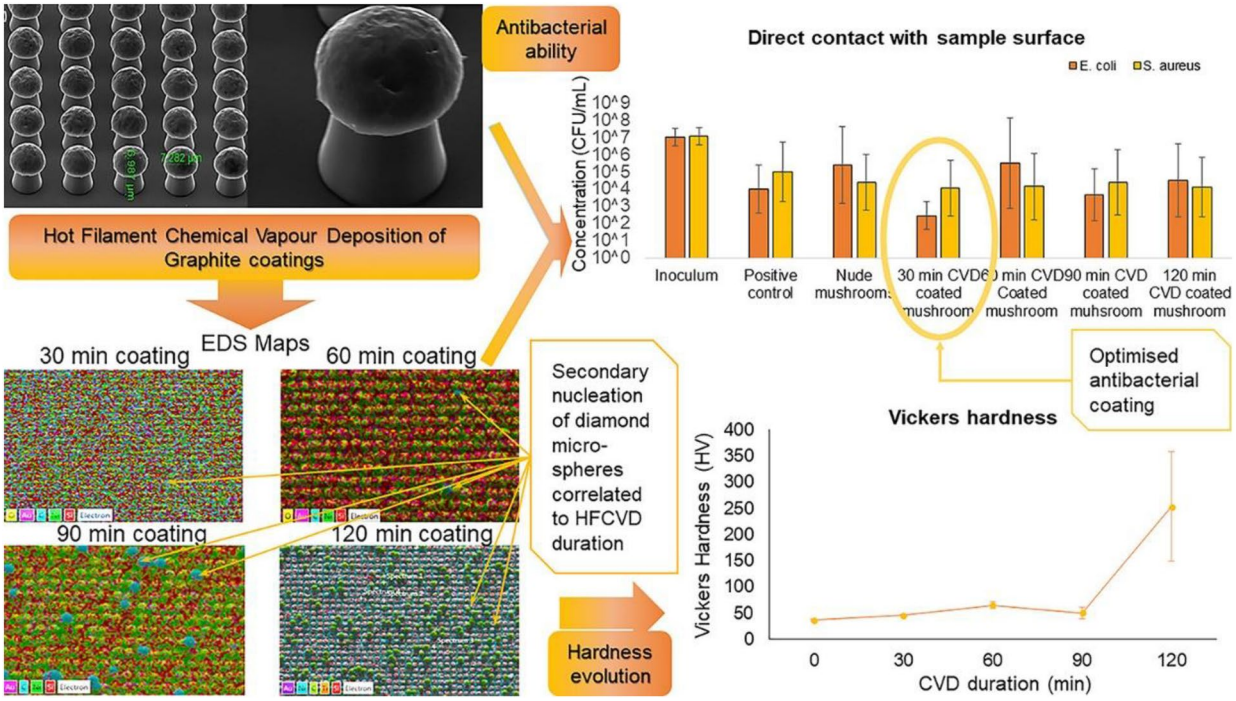

Figure 2. Influence of the presence of diamond microspheres on top of mushroom microstructures coated with Graphite on the antibacterial properties against *E. coli* and *S. aureus* and the Vicker's Hardness of the coating. Reproduced from [31] with permission.

surface of the film tend to form nanoparticles agglomerates with time, increasing the size of diamond particles able to interact with the bacteria and preventing them to penetrate the cells [217]. Moreover, Beranová et al. demonstrated that diamond nanoparticles spread on agar plates significantly reduced the growth of *E. coli* with a concentration dependence and a dependence of the ratio between the number of diamond nanoparticles and the number of *E. coli* bacterial cells in the media. Proper and satisfactory growth inhibition was observed for agar plate spread with diamond nanoparticles concentration above 30 µg/L and total bacterial growth inhibition was observed for agar plates spread with 60 µg/L of nanodiamonds. Concerning the ratio of the number of nanodiamond particles per *E. coli* bacterial cell, the growth inhibition was higher than 80% above 7 NDs per 1 *E. coli* cell and higher than 95% above 15 NDs per 1 *E. coli* cell. It suggests that knowing the concentration of pathogen in a media would allow tailoring very precisely the concentration of antibacterial particles needed to inhibit its growth [157]. Based on a similar investigation, Chwalibog et al. also determined that ND had a Gram-dependent growth inhibition effect and, despite the cidal effect recorded against the Gram-negative *E. coli* bacteria, the Gram-positive *Staphylococcus aureus* appeared undamaged after contact with NDs. The authors explained this difference of effect by the positive zeta potential of their ND [218].

1.1.3. A low number of diamond-based antibacterial composites investigated

As diamond films and diamond particles themselves have great antibacterial properties in general compared to antibiotic controls, only a low number of diamond-based composites were investigated as it increases the costs and times of production that would not be needed. It was mainly investigated in the cases where as-grown diamond films or particles didn't have high antibacterial properties but the as-grown films or particles shown superior mechanical, electrical or chemical properties that would make the additional cost of a doping process acceptable.

For instance, in the case of diamond films with nanocrystalline diamonds, their intrinsic properties are interesting enough to create a composite with Silver nanodroplets embedded in the UNCD film [210] (Figure 3). In that case, the antibacterial properties are not expected from the UNCD film, and Merker et al. demonstrated that the crystalline size was too small to have any cidal properties. They are expected from the silver nanodroplets that are successfully able to release antibacterial silver cations in the media against both Gram-positive and Gram-negative bacterial strains. The cation release process is highly dependent on the UNCD capping layer and the thinner the capping layer, the larger the concentration and the faster the silver cations are released. It follows that the antibacterial properties of this diamond-based composite are tailorable depending on the number of silver cations and the duration of silver cations released needed. With the addition of the strength and the duration of the antibacterial property, this composite compensates the extra-costs and steps needed in the fabrication process [210].

Following the same idea, diamonds nanoparticles were functionalised using silver nanoparticles. Xu *et al.* directly synthesised silver nanoparticles with a narrow size on

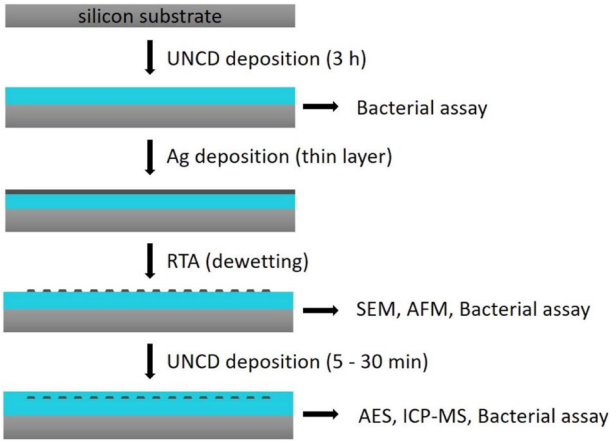

Figure 3. Process of UNCD-Ag-UNCD composites and the different investigations made at each step. Bacterial assays were performed on the UNCD surface, after silver deposition and dewetting, and once again after the UNCD top layer. Reproduced with permission from [210].

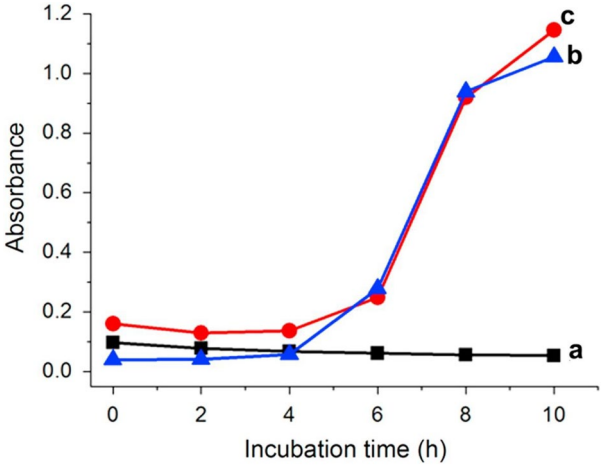

Figure 4. Growth curves of *E. coli* bacterium in broth containing (a) 6.6×10^{-4} wt% Ag/ND, (b) 6.6×10^{-4} wt% ND and (c) H2O demonstrating the efficiency of Ag-ND at very low concentration against *E. coli* growth. Reproduced from [219] with permissions.

the ND particles using the reduction of $AgNO_3$ by Polyvinylpyrrolidone. The formed nanocomposite displayed high bactericidal activity toward the Gram-negative *E. coli* bacterial strain at very low concentration in the cultivation media [219] (Figure 4). As concerns are developing concerning the rise of bacterial resistance against Silver [30, 220–231] and Copper [229, 232–244] as well as concerns about the impact of heavy metal on the spread and development of antibiotic resistance genes [120, 245] recently, the creation of diamond composites with Cu and/or Ag NPs immobilised of their surface could be a valid strategy to avoid this resistances to develop and to reduce the needed amount of Cu and Ag to display satisfactory antibacterial properties.

As DLC film does not show incredible antibacterial properties by themselves, despite the diamond films being exceptionally efficient in certain conditions, a strategy to reduce the cost of diamond film production could be the introduction of diamond particles into DLC films. Gutierrez et al. investigated this idea and loaded a DLC film using DND nanoparticles. They demonstrated that a diamond-DLC composite was able to reach 95% of bacterial growth reduction with direct contact during 6 h and SEM images show a proper cidal activity with *E. coli* membrane disruption and cell content leakage. However, after 18 h of contact, this antibacterial activity dropped to about 20% of bacterial growth reduction and was attributed to the formation of ND clusters, diminishing their ability to penetrate the bacterial cell [217]. It suggests that this composite might be interesting to join the best of both DLC and diamond antibacterial properties, but it will need additional investigation to offer sustainable antibacterial properties. For instance, a strategy to immobilise the ND particles in the DLC film could avoid the formation of the ND aggregates and protect their antibacterial properties among time.

1.1.4. Antibacterial diamond-like carbon films and diamond-like carbon-based composites

Diamond-Like Carbon (DLC) films were also investigated because of their structures near the diamond films' and their lower costs and time of production thanks to the higher deposition rate obtainable [246]. As a more economically-sustainable suggestion for the future of efficient antibacterial, chemically inert, resistant and biocompatible films, they are an interesting alternative to proper diamond films especially for biomedical devices [247]. Anti-adhesive properties were investigated as well as bactericidal and antibiofilm properties.

Similar to diamond films, the structures, the internal bonds as well as the hydrogen content of DLC films are influencing the bacterial adhesion to their surfaces [248, 249]. These parameters influence the chemical inertness and the wettability of the film that are believed to be involved in the bacterial adhesion process [250]. The bacterial adhesion is dependent on different forces including *Van der Waals* interactions, and the hydrophilic interactions. For instance, the decrease in the sp^3/sp^2 ratio in the DLC film is followed by a slight decrease in the bacterial adhesion. Moreover, the presence of –H polar bonds at the surface of the DLC film can increase the surface hydrophilicity and can promote the bacterial adhesion. They calculated that the lower the C–H bonding at the film surface, the lower the surface free energy and finally, the lower the bacterial adhesion on the DLC films. The surface roughness wasn't reported as a significant parameter in the bacterial adhesion process [248, 249]. Other parameters are important to avoid bacterial adhesion and only moderate bactericidal activities: The deposition parameters [249], direct contact with the DLC film surface [217, 246, 248] (Figure 5).

However, surface functionalisation and the development of composites based on DLC were able to improve dramatically their antibacterial properties. DLC films were successfully doped with silver [249, 251–259], Copper [256, 260–263], Silicon [264], Fluorine [264–268], and Metal oxides (ZnO and TiO_2) [34, 269–279] (Table 2).

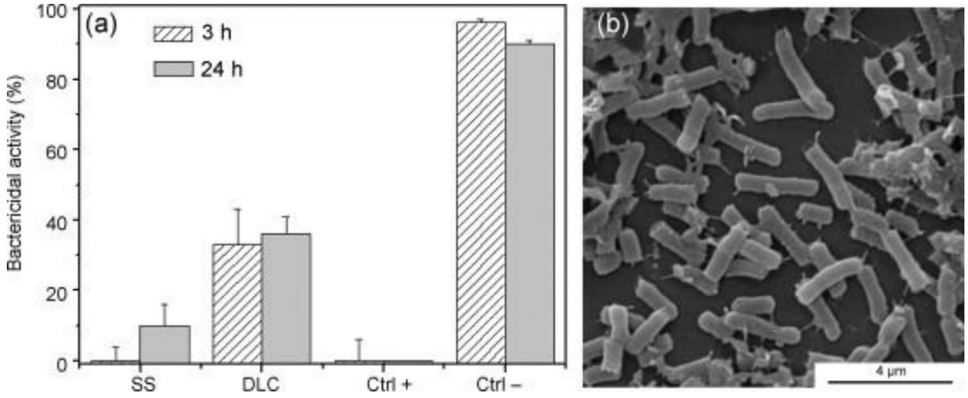

Figure 5. (a) Antibacterial properties of DLC film coated on Stainless Steel substrate after 3 h and 24 h incubation versus uncoated Stainless Steel, Gentamicin, an antibiotic and sterile distilled water. (B) SEM observations of *E. coli* in contact with DLC coating after 3 h contact. Reproduced with permission from [246].

2. Antibacterial mechanisms of action

2.1. Importance of the surface functionalisation for antibacterial applications

2.1.1. Influence of simple surface groups

Nanodiamonds are also investigated in suspensions with various surface functionalisation for their antibacterial properties. Among them, partially oxidised nanodiamonds were investigated by Wehling et al. The authors obtained different surface functionalisation and zeta potentials using various standard pretreatments on detonation nanodiamonds. Afterwards, they processed on antibacterial assays and determined that nanodiamonds with a grade 01 purity, a negative zeta potential and having oxygen-containing groups at their surfaces were especially efficient against both Gram-negative and Gram-positive bacteria in aqueous conditions, independently of their pretreatments (Figure 6A). Interestingly, a high purification of the ND obtained using the detonation technique were not able to develop antibacterial properties anymore. Thus, they tested the impurities obtained with the detonation technique which did not lead to any answer until they explored the difference of the surface oxidation between the two purification grades. The extra purified nanodiamonds have less oxidised surface functions than the G01 nanodiamonds, and a strong correlation between the amount of oxidised surface function on the nanodiamond surface and the bacterial killing rate was demonstrated. It proves that the importance of the surface functionalisation for efficient bacterial killing is as important for ND suspended in aqueous media than immobilised in antibacterial films. From their data, the anhydride acid groups, negatively charged, are the most important in the bacterial killing process thanks to their higher reactivity. As a confirmation, the lower reactivity of carboxylic groups made ND less able to kill bacteria. Wehling et al. attributed the difference of efficiency to the difference in the surface isotropy and the homogeneity of the surface charge distribution, the more interesting being an anisotropic surface with an inhomogeneous surface charge distribution [175]. Other studies were carried about the nanodiamonds surface functionalisation and reviewed by Szunerits et al. and confirmed the results of Wehling et al. [175] concerning the importance of the oxidation state and the charge of the surface groups of nanodiamonds [173]. Although less able to kill bacteria than other oxidised surface groups, Chatterjee et al. show that the cidal properties of carboxylated NDs are due to their ability to bind with the bacterial cell wall, change its protein structure (proven with Raman spectroscopy) and leads to internal cell content leakage. The mechanism is also demonstrated different from lysozyme treatment and lysis confirming the role of the carboxylated NDs in the cell wall destruction [281].

Additionally to oxidised surface groups, Budil et al. investigated simpler surface functionalisation such as –H, –F, and –O on NCD films. NCD films with –O surface termination did not show any anti-adhesive effect against *E. coli* however, in mineral medium only, NCD films terminated with –H and –F were able to reduce the bacterial adhesion by about 50%. However, in LB broth containing organic molecules, these surface groups seem to favour the bacterial adhesion. It suggests that the passivation occurring in organic media implies organic molecules that the bacterial cell can use as an adherence substrate and that in mineral media that these surface groups are repulsive to the bacterial membranes [206]. Dunseath et al. also demonstrated that among the different tested surface functions (–H, –F, $–NH_2$, and –O), the amount of dead adhered bacteria was a function of the hydrophilicity of the diamond film surface (Figure 6B). In other terms, the more the surface is hydrophobic, the higher number of dead adhered bacteria [158].

Robertson et al. studied a more exotic surface function using Germanium. The higher polarity of the Carbon-Germanium bond increased the surface free energy of the DLC film surface, decreasing the surface biofouling with *P. aeruginosa* bacteria. Additionally, they demonstrated a Gram-dependent cidal activity, with 90% of Gram – bacteria growth reduction and no significant effect against Gram-positive bacteria (Figure 6C). Moreover, Ge-DLC

Table 2. Summary of the diamond-based and DLC-based antibacterial materials with their compositions, the expected antibacterial element, the bacterial strains tested, the mechanism of action when known, the type of antibacterial properties, the lowest efficient bactericidal or antibiofilm concentration when applicable and additional interesting characteristics. Abbreviations: N/A: Not Applicable, NCD: Nanocrystalline Diamond, MCD: Microcrystalline Diamond, UNCD: Ultra Nanocrystalline Diamond, DLC: Diamond-Like Carbon, ND: Nanodiamond, MRSA: Methicillin-Resistant S. aureus.

Main material	Material and composition	Antibacterial element (if known)	Targeted bacteria	Gram Type	Mechanism of action (if known)	Antibiofilm?	Bactericidal?	Lowest efficient concentration (if applicable)	Additional characteristics	Reference
Diamond film	Diamond film with H and F surface termination	H and F termination in mineral medium	*E. coli*	–	Antiadhesive thanks to hydrophobic properties	Yes		N/A		[206]
	Black diamond coating on black silicon nanoneedles	H, O, NH_2, F surface termination and nanoneedle shape	*E. coli*	–	Hydrophobic repelling, physical membrane disruption	Yes	Yes	N/A		[158]
	Black diamond coating on black silicon nanoneedles	Nanoneedle shape	*E. coli, Streptococcus gordonii*	–,+	Physical membrane disruption	Yes (*E. coli*)	Yes (*E. coli*)	N/A		[164]
	Boron-doped diamond coating on black silicon nanoneedles	Nanoneedle shape	*P. aeruginosa*	–	Physical membrane disruption	Yes	Yes	N/A	Good electrode for Dopamine sensing in Uric Acid excess	[207]
	NCD and MCD film	The grain size of the film	*P. aeruginosa*	–	Super-hydrophobia repelling and killing the bacteria or the semiconductivity for NCD	Yes (NCD)	Yes (NCD)	N/A		[208]
	UNCD films with embedded Ag	Silver cation release	*E. coli, B. subtilis*	–,+	Silver-related metabolism disturbance and membrane destabilisation	N/A	Yes	N/A	Best material obtained with 5min UNCD caping	[210]
	NCD film, F-NCD film	O, F surface termination	*E. coli*	–	Metabolic disturbance, oxidative stress, electrostatic repulsion	Yes	Yes	N/A	F-NCD film shows better antibacterial properties	[209]
	Fluorinated micro- and nanostructured hierarchical diamond film	F surface termination, hierarchical patterned surface	*P. aeruginosa, E. coli*	–,–	Electrostatic repulsion, Membrane stretching	Yes	Yes	N/A		[280]
DLC films	High deposition rate DLC film	DLC	*E. coli*	–	Interaction between DLC and bacterial cell	No	Moderate (30%)	N/A		[246]
	DLC film	DLC structure, chemical bonds and H content	*E. coli, P. aeruginosa, Salmonella typhimurium, S. aureus*	–,–,+,+	Direct contact between nanocarbon aggregates and bacterial cell	No	Moderate (25-55%)	N/A		[248]
	Multilayer DLC coating	DLC	*P. aeruginosa, S. aureus*	–, +	direct contact with the surface	Yes (*P. aeruginosa)*	No	N/A		[250]
Nanodiamonds	ND	ND	*E. coli*	–	ND binding to cell wall and flagella, metabolic disturbance, ND entering the cell	N/A	Yes, concentration dependence	4ng ND per 1 *E. coli*: 25% of bacterial growth inhibition, 7 to 15 ng ND per 1 *E. coli*: >85% of bacterial growth inhibition, 22 to 44 ng of ND per 1 *E. coli*: 100% inhibition of bacterial growth		[157]

(Continued)

Table 2. Continued

	Ultrafine carboxylated ND (5 nm)	carboxyl surface function	*E. coli*	–	Destruction of the bacterial cell wall by ND binding	N/A	Yes	Not tested	Here, a different mechanism is involved than for lysozyme treatment or lysis	[281]
	DLC film doped with ND	ND	*E. coli*	–	Disruption of bacterial cell wall	N/A	Yes but decreased over time (18 h) because of the rise of ND aggregates	Not tested	High corrosion resistance	[217]
	Partially oxidised ND of two purity grade obtained with annealing in air atmosphere for negatively charged ND or in H_2 atmosphere for positively charged ND	ND surface functions with positive or negative charges (zeta potential ranging from -77 to + 80 mV depending on pretreatment)	*E. coli, B. subtilis*	–,+	Lower-grade purity and positively charged ND interact with bacterial membrane, Negatively charged ND penetrate the cells and disturb the metabolism	N/A	Yes for negatively charged and raw ND	50 mg/L of ND- and ND raw, 500 mg/mL for ND +		[175]
Functionalised ND	Nanodiamond Silver composite	Ag	*E. coli*	–	Oxidative stress and metabolic disturbance bu Ag cations	N/A	Yes	6.6 x 10^{-4} wt% of Ag-ND	Pristine ND didn't show bacterial growth reduction for the same concentration	[219]
	Methol modified ND	Menthol	*E. coli, S. aureus*	–,+	Not investigated	Yes, with concentration dependence	No	Against *S. aureus*: 70% biofilm inhibition for 1 µg/mL, 80% for 10 µg/mL, 90% for 100 µg/mL. For *E. coli*: 50% biofilm inhibition for 1 µg/mL, 70% for 10 µg/mL, 95% for 100 µg/mL.	All tested concentration inhibit *E. coli* biofilm better than the antibiotic.	[216]
	Mannose-ND	Mannose	*E. coli*	–	Selective binding between Mannose and type 1 FimH protein of *E. coli* pilii preventing their adhesion to yeast or human bladder cell and biofilm formation	Yes	No	> 80 µM for a minimum of 60% biofilm inhibition,		[156]
	Glyco-ND	Monomannoside and trimannoside surface functionnalisation	*E. coli*	–	Selective binding between saccharides and type 1 FimH protein of *E. coli* pilii forming filtrable aggregates	N/A	No		80 µg/mL of Mannosylated ND allows the filtration of 1000 µg/mL of *E. coli* through a conventional 10 µm filter	[163]

Table 2. Continued

	Trimannose-ND	Trimeric cluster thiomannosides surface functionalisation	*E. coli*	–	Selective binding between Mannose and type 1 FimH protein of *E. coli* pilii preventing their adhesion to yeast or human bladder cell and biofilm formation + Biofilm disruption	Yes	No	21 µM of Trimannose-ND		[167]
DLC composites	Ag DLC (3.8 to 27 at% of Ag)	Silver cation release	*S. aureus*	+	Silver-related metabolism disturbance and membrane destabilisation	N/A	Yes	N/A	Ag content in DLC film does not influence the antibacterial properties strongly	[251]
	Ag DLC (Ag: PVP 1: 2, Ag: PVP 1: 10 and Ag: PVP 1: 20)	Silver cation release	*S. epidermidis, S. aureus, P. aeruginosa*	+, +, –	Silver-related metabolism disturbance and membrane destabilisation	Yes	Yes (better against *P. aeruginosa,* least efficient against *S. aureus)*	N/A	Increasing growth inhibition with increasing silver content	[257]
	Ag DLC	Silver cation release	*S. epidermidis*	+	Silver-related metabolism disturbance and membrane destabilisation	Yes (depends on deposition method)	Yes	N/A	Plasma immersion ion implantation method provided better Ag-DLC antibacterial coatings than direct ion implantation method	[256]
	Ag DLC (3.4 at.% of Ag)	Silver cation release	*S. aureus* (including *MRSA)*	+	Silver-related metabolism disturbance and membrane destabilisation	Yes	Yes	N/A	Wound infected with *MRSA* healed faster with the Ag-DLC composite	[255]
	Ag DLC (0.46 at.%, 3.12 at.% and 6.43 at.% of Ag)	Silver cation release	*S. aureus* (extracted from human and animals infected wounds)	+	Silver-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	DLC-Ag composites with 3.12 at.% of Ag were the most efficient	[252]
	Ag DLC (Ag/C ratio: 0.07, 0.20, 1.05, 2.50)	Silver cation release	*E. coli*	–	Silver-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	No significative influence of Ag content	[253]
	Ag DLC (3 min and 5 min Silver deposition)	Silver cation release	*S. aureus*	+	Silver-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	Significantly better antibacterial growth reduction for the sample containing the highest silver content	[259]

Table 2. Continued

Ag DLC (4.5 at.% and 5.2at.% of Ag)	Silver cation release	*Streptococcus sanguinis*	+	Silver-related metabolism disturbance and membrane destabilisation	N/A	Yes	N/A	The antibacterial killing effect is dependant on the ability of silver to release through the covering layer (max 10 nm)	[258]
Ag DLC (2.1, 6.1 and 14.3 at.% of Ag)	Silver cation release	*E. coli*	–	Silver-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	Strong positive correlation with the Silver atomic percentage in the film	[249]
Ag DLC	Silver cation release	*C ampylobacter jejuni, L isteria monocytogenes*	–, +	Silver-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	Bacterial inhibition is achieved in only 15 to 30 min against *C. jejuni* while it took 24 h against *L. monocytogenes*	[254]
Cu DLC (0.39 and 1.42 at.% of Cu)	Copper cation release	*E. coli*	–	Cu-related metabolism disturbance and membrane destabilisation	Yes	Yes	N/A	No influence of the Cu content	[263]
Cu DLC	Copper cation release	*S. epidermidis*	+	Cu-related metabolism disturbance and membrane destabilisation	Yes	No	N/A		[256]
Cu DLC (30 to 55 wt.% of Cu)	Copper cation release	*Porphyromonas gingivalis*	–	Cu-related metabolism disturbance and membrane destabilisation	Not investigated	Yes	N/A	A positive correlation between Cu film content and bactericidal activity is reported	[262]
F-DLC (from 7.91 to 16.53 at.% of F)	Hydrophobic repellence thanks to F addition	*E. coli*	–	Lower surface free energy reducing bacterial adhesion	Yes	No	N/A	Importance of the deposition method: Direct deposition gives better antibacterial properties than with remote control	[265]
F-DLC (from 0.9 to 2% of F)	Hydrophobic repellence thanks to F addition	*E. coli*	–	Lower surface free energy reducing bacterial adhesion	Yes	No	N/A	Positive correlation between antiadhesive properties and F content in the film	[266]

Table 2. Continued

F-DLC and O-F-DLC	Hydrophobic repellence thanks to F addition	*S. aureus, E. coli*	+,–	Lower surface free energy reducing bacterial adhesion	N/A	Yes against *S. aureus* for all samples. Yes for *E. coli* only for O-F-DLC with the shortest plasma treatment)	N/A	[267]
F-DLC (6.5, 20.7 and 39.2% of F)	Hydrophobic repellence thanks to F addition	*Klebsiella pneumoniae*	–	Lower surface free energy reducing bacterial adhesion	Yes	Not investigated	N/A	Strong positive correlation with the F percentage in the film [264]
F-DLC (5.44, 17.43, 24.09, and 30% of F)	Hydrophobic repellence thanks to F addition	*S. aureus, E. coli*	+,–	Lower surface free energy reducing bacterial adhesion	Yes	Not investigated	N/A	Antibiofilm for F content superior to 17.43%. No cytotoxicity reported [268]
Si-DLC (3.7, 9.7 and 19.2% of Si)	Antiadhesive performance thanks to Si addition	*K. pneumoniae*	–	Lower surface free energy reducing bacterial adhesion	Yes	Not investigated	N/A	Antiadhesive properties are non-linearly dependent on the Si content [264]
TiO_2-DLC biomineralised film (0.1 and 0.3 g/L of TiO2)	Synergy between hydroxyapatite and TiO_2 antibacterial activities	*S. aureus*	+	TiO_2 oxydative stress and antiadhesive properties enhanced by hydroxyapatite crystal adhesion	Yes	Yes	N/A	Positive correlation between the TiO_2 content and the antiadhesive and antibacterial activity [282]
TiO_2-DLC (0.1, 0.5, 1.0 g/L of Anatase)	Anatase crystals	*E. coli*	–	TiO_2 oxidative stress and antiadhesive properties	Yes	Yes	N/A	Strong correlation between Anatase content in the film and bactericidal activity [279]
ZnO-DLC	Zinc cations release	*S. aureus* (resistant to Methicillin and Oxacillin), *S. epidermidis*	+,+	Zinc associated oxydative stress and metabolic disturbance	N/A	Yes, especially against Methicillin and Oxacillin resistant *S. aureus*	N/A	pH-responsive antibacterial film, able to detect the bacterial-related acidosis and display efficient antibacterial activity at moderately acidic pH (6.4) [269]
Ge-DLC with multilayer DLC	Ge-C polar bonding creating higher surface energy	*P. aeruginosa, S. aureus*	–,+	Increased surface free energy decreasing the bacterial adhesion and cidal activity of Ge	Yes	Yes, only against *P. aeruginosa*	N/A	[250]

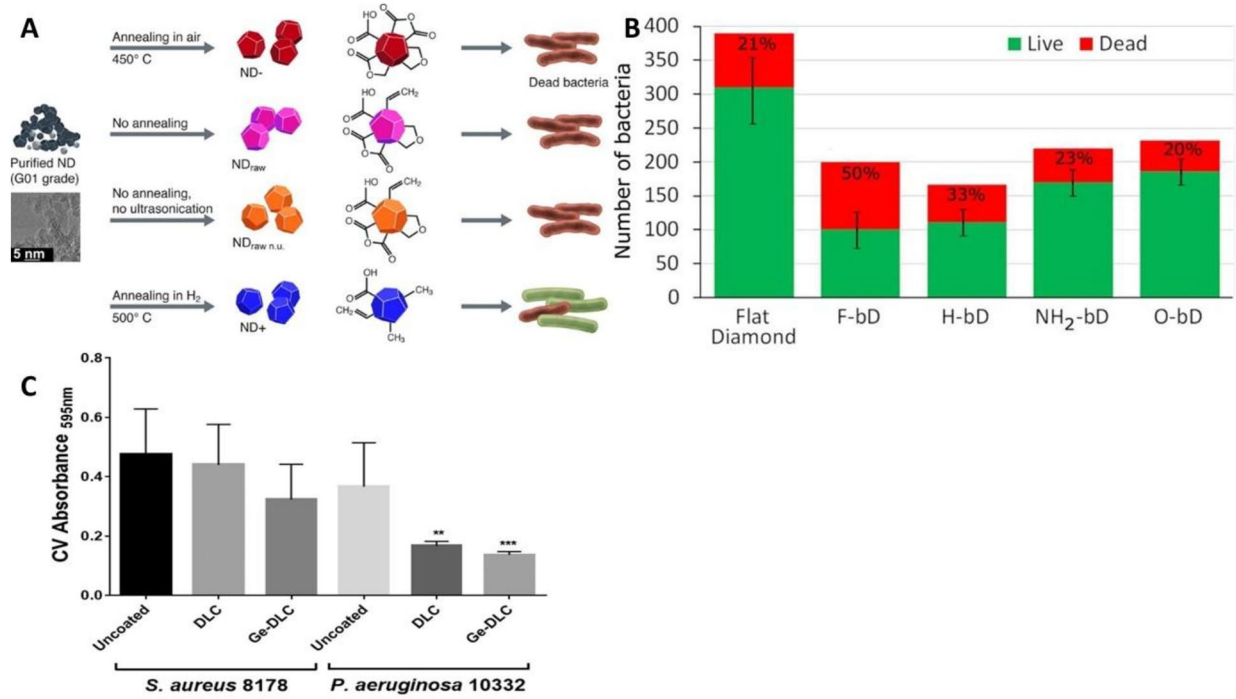

Figure 6. (A) Negatively charged ND- and NDraw/NDraw n.u. were shown to exhibit strong antibacterial properties under aqueous conditions, while ND + caused bacterial death only at high ND concentrations. Reproduced with permissions from [175] (B) Bacterial viability on surfaces with the different terminations, compared to that of the H-terminated flat diamond control. Numbers of live (green) and dead (red) cells are indicated, together with the corresponding percentage of dead cells. The uncertainties in the measurements are shown as error bars representing one standard deviation of the number of dead cells based upon 4 repeats of the experiment. Reproduced with permissions from [158]. (C) Effect of DLC and Ge-DLC on 24 h biofilm formation of *P. aeruginosa* and *S. aureus*. Comparison of biofilm formation on uncoated SS316, DLC coated SS316 and germanium doped DLC coated SS316 with *P. aeruginosa* and *S. aureus*. Data are mean ± Standard deviation. $n = 3$, $^{***}p < 0.001$, $^{**}p < 0.01$. Reproduced with permissions from [250].

coating was able to reduce *P. aeruginosa* biofilms of more than 60% compared to Stainless Steel. Despite the difference with undoped DLC coating wasn't significant in terms of quantitative analysis, the SEM investigation of the *P. aeruginosa* biofilms developed on both DLC and Ge-DLC coatings show a significant difference between them: a proper cidal activity was observable only on Ge-DLC coating, suggesting this surface functionalisation was adding cidal properties to DLC film [250].

2.2. Surface functionalisation with molecules

2.2.1. Glycan-surface functionalised nanodiamonds

Additionally to "simple" chemical functions, nanodiamonds can also be functionalised with larger molecules. In their review, Szunerits et al. analysed the interest of glyco-conjugate nanodiamonds against *E. coli*. *E. coli* is a Gram-negative bacteria possessing pilii terminated with an adhesive FimH protein having a specific affinity for Glycosaccharides and Mannose (Figure 7A). Using click-chemistry, it is relatively easy and fast to obtain mannose-functionalised nanodiamonds (Mannose-ND) with different amount of mannose molecules per nanodiamonds and Diels-Alder chemistry allows the formation of Saccharide functionalised nanodiamonds. First, it is interesting to note that *E. coli* was able to bind with the Mannose and saccharide molecules on the surface of the nanodiamond. Second, their binding to this Mannose-ND reduced the ability of *E. coli* to adhere to mammal bladder cells (Figure 7B), avoiding the formation of biofilms responsible for mammals' urinary tract infections (Figure 7C)[156]. Thirdly, the interaction of the type 1 FimH on *E. coli* pilii with the saccharides on the ND produces a precipitate that can be easily filtered from the growth media using a 10 µm filter and the ND could finally be recovered after filtration in an easy-step (Figure 7D) [163]. Finally, it was observed that the number of mannose molecules on the ND surface were of interest. NDs bearing 3 mannose molecules at their surfaces were able to develop an antibiofilm ability higher than three times the ability of NDs functionalised with single Mannose molecules, suggesting a synergetic action of the mannose molecules at the nanodiamonds surface [167]. These results are interesting for the development of antibacterial drugs alternative to antibiotics [173].

2.2.2. Essential oil surface functionalised nanodiamonds

Other molecules were also investigated, such as essential oils. One of the most braking points of essential oils is their volatility leading to a loss of most of the active compounds before arriving at the targeted place. The fixations of the active compound on the NDs' surfaces reduced dramatically the volatility. For instance, the menthol molecule, cyclic terpene alcohol being the main compound of *Mentha canadensis L.* essential oils, was attached on NDs (Menthol-ND) (Figure 8A, B).

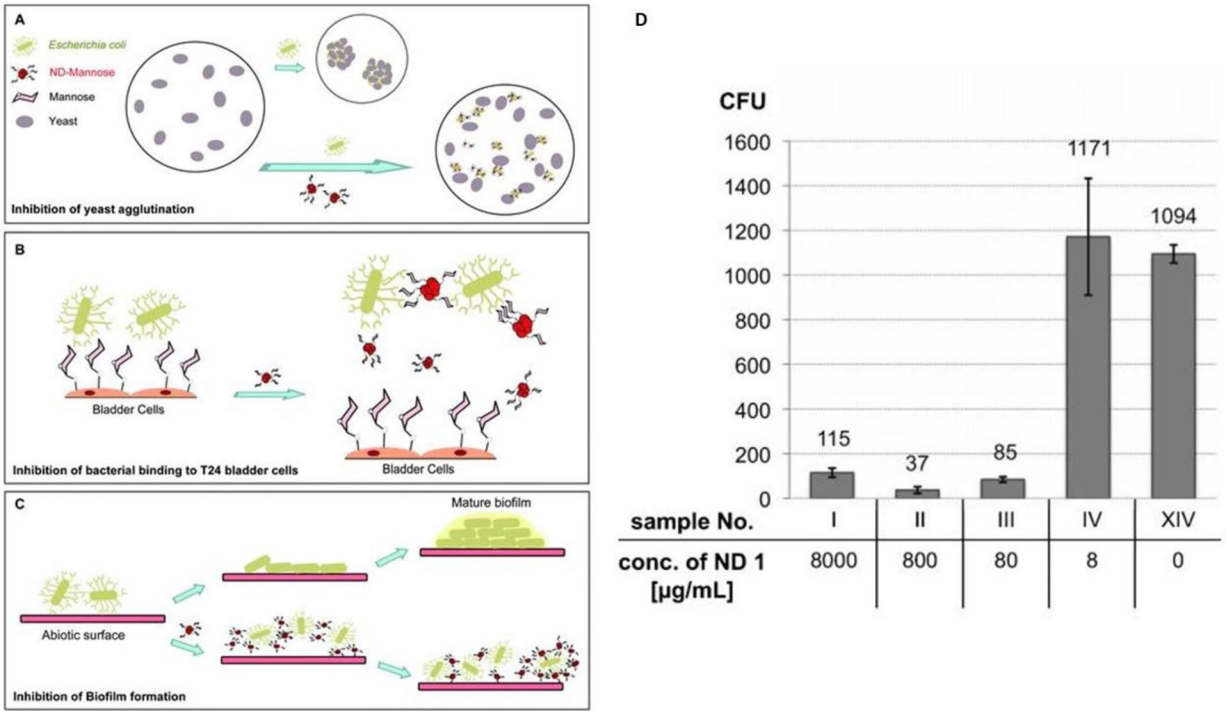

Figure 7. Schematic representation of ND-mannose ability to counteract FimH-mediated adhesion. (A) Capacity of ND-mannose to interfere with type 1 fimbriae-mediated adhesion to eukaryotic cells was demonstrated using yeast agglutination inhibition assay as well as (B) inhibition of *E. coli* adhesion to bladder epithelial cells. (C) In addition, ND-mannose was demonstrated to be inhibitors of *E. coli* biofilm formation. (D) The agglutination-filtration experiments with *E. coli* show that the addition of just 80 µg mL^{-1} of the mannosylated ND 1 is sufficient to efficiently remove 1000 µg mL^{-1} of fimbriated bacteria PKL1162 from the solution by filtration through a conventional filter with 10 µm pore size. Reproduced with permissions from [156].

Turcheniuk et al. demonstrated a moderate but concentration-dependent direct killing effect toward both bacteria tested (Figure 8C, D), however, Menthol-ND had a better antibiofilm effect against both bacteria than ND alone or the dedicated antibiotic used as a control (Figure 8E, F) [216]. Despite the moderate proper antibacterial effect, the reduction of the biofilm formation is of great interest since these macrostructures formed of a great number of bacteria reunited with Extra-Polymeric Substances in a superstructure is harder to kill than single bacteria. It could be seen as a first step to simplify the treatments and shorten the treatment length of certain infections, using fewer antibiotics, for shorter periods.

2.2.3. Importance of the surface structure: physical antibacterial mechanism of action

The antibacterial properties appear *via* different mechanisms *via* the surface groups and chemical functions, the chemical mechanism of action is mainly investigated. Concerning the physical antibacterial of action, the surface structuration of the diamond films is an important component of the bacterial membrane stretching and the cell content leakage, leading to bacterial death. From the literature, two antibacterial nano structuration using diamonds were investigated. Firstly, the chemical vapour deposition process is used to produce micro and nanostructured hierarchical diamond films that reproduce the shape of lotus leaves' surface able to avoid biofouling and water damages. Biofouling is a process in which bacterial cells and organic compounds cover a surface and leads finally to bacterial attachment and biofilm formation covering all the surface. It also leads to corrosion and deterioration of equipment used in biological media and marine environment. The hierarchical film developed by Wang et al. looks like numerous little domes made of fluorinated-diamond covering a flat surface, the substrate, which can be of different chemical nature (Titanium, silicon, or glass). This micro and nanostructuration made with diamond confers to the surface superhydrophobicity (surface contact angle comprised between 161° and 171°, depending on the substrate, the better being the silicon) and decreased the green algae biofouling by 95%. Moreover, the association between the Fluorination and the super hydrophobia conferred by the structuration reduces the marine *P. aeruginosa* and *E. coli* adhesion of 90–99% on the structured surface. The few bacteria that were attached to the film were dead accordingly to the live/dead fluorescence assay (Figure 9). The authors explained it by the presence of air trapped at the surface of the structured diamond film which prevents the biofilm formation [280].

The most investigated surface nanostructuration based on diamond films is nanospike. It was investigated after May et al. realised that black silicon nanospikes offered an incredible bactericidal effect, especially against large motile bacteria such as *E. coli* but had the disadvantage of being easily breakable. The addition of black diamond coating on the surface of the black silicon nanospikes allowed higher resistance

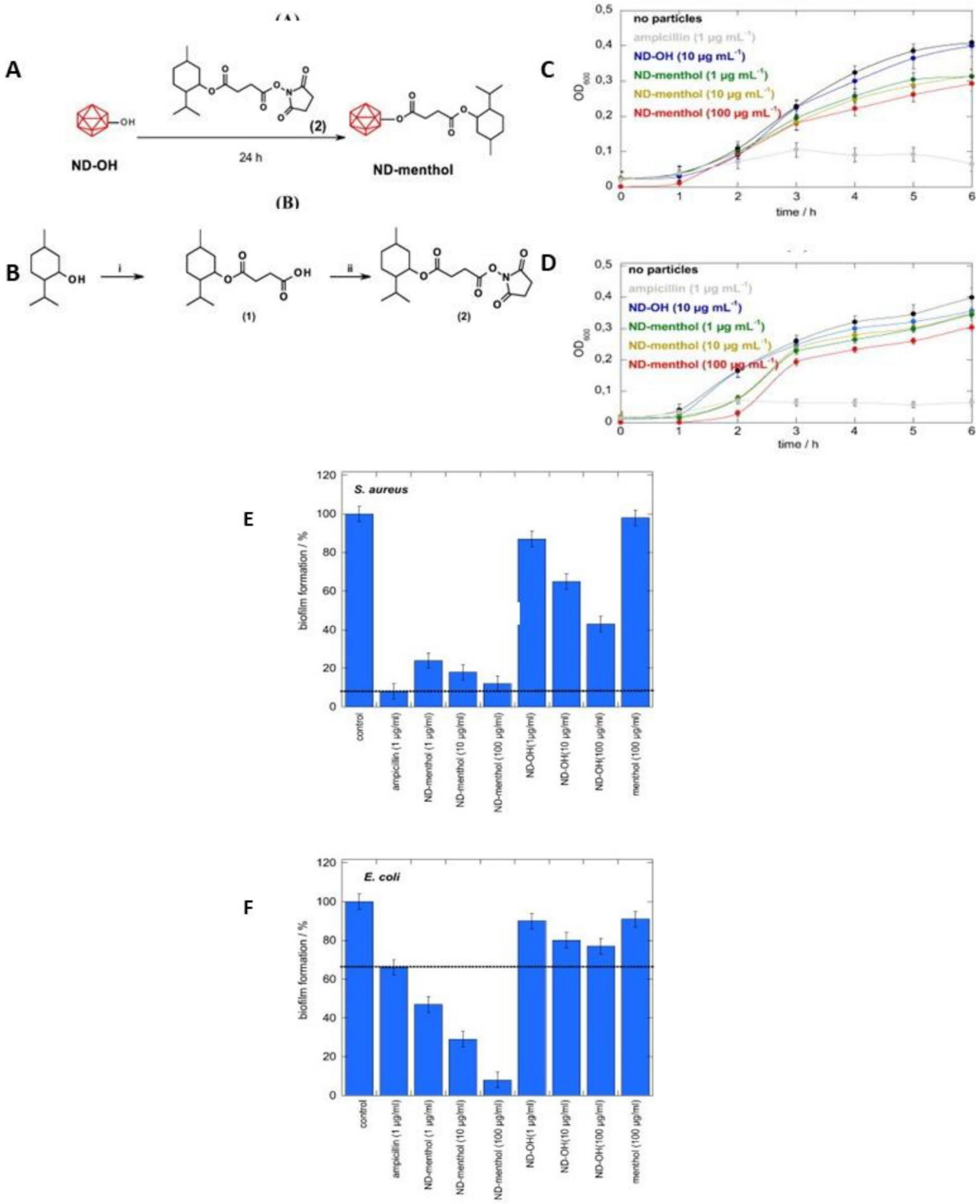

Figure 8. (A) Schematic illustration of the stepwise chemical functionalization of nanodiamond particles (ND) to give the target ND-menthol cluster; (B) synthetic route to menthol derivative (2): (i) succinic anhydride, 4-DMAP, CHCl3, reflux, overnight, 84%; (ii) NHS, DCC, CH2Cl2, r.t, overnight, 95%. Growth curves of (C) S. aureus and (D) E. coli in the presence of ND-OH (10 µg mL^{-1}), ampicillin (1 µg mL^{-1}) and ND-menthol at 1, 10 and 100 µg mL^{-1}. Biofilm formation of (E) *S. aureus* and (F) *E. coli* in the absence and presence of ND-menthol (1, 10, 100 µg mL^{-1}), ND-OH (1, 10, 100 µg mL^{-1}), ampicillin (1 µg mL^{-1}) and menthol (100 µg mL^{-1}). Reproduced with permissions from [216].

to abrasion and higher hardness (Figure 10A), with a superior bactericidal property combining the physical membrane disruption of the nanospikes with the chemical effect of diamond surface functionalisation against *E. coli* and *P. aeruginosa* (Figure 10) [158, 207]. The authors also demonstrated that the space between the nanospikes (also called areal density) was of great importance to interact and disrupt the bacterial membranes and found the optimum value for *E. coli* and suggestions for smaller bacteria such as *S. gordonii* despite their smaller size, thicker membrane and lack of motility [164].

Both nanostructured surfaces based on diamond proved they can improve the bactericidal and anti-

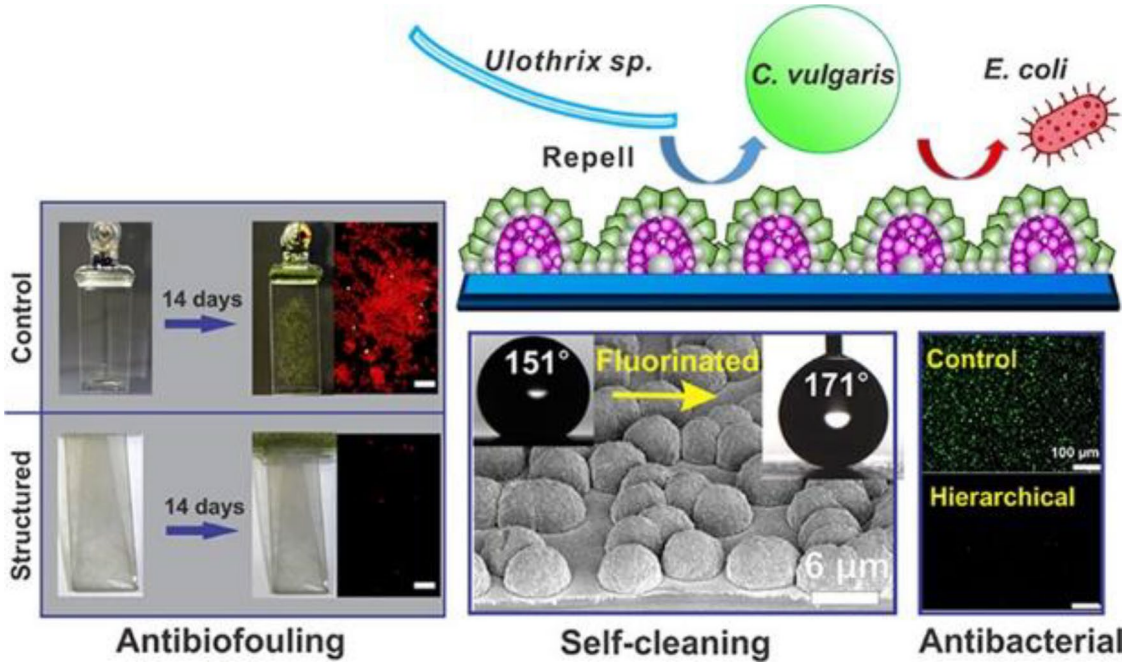

Figure 9. Schematic representation of the micro and nano hierarchical structure of the diamond film and its effect against algae and bacteria. Antibiofouling is very efficient on 14 days and the self-cleaning and antibacterial properties are related to the highest hydrophobicity and the surface fluorination. Reproduced with permissions from [280].

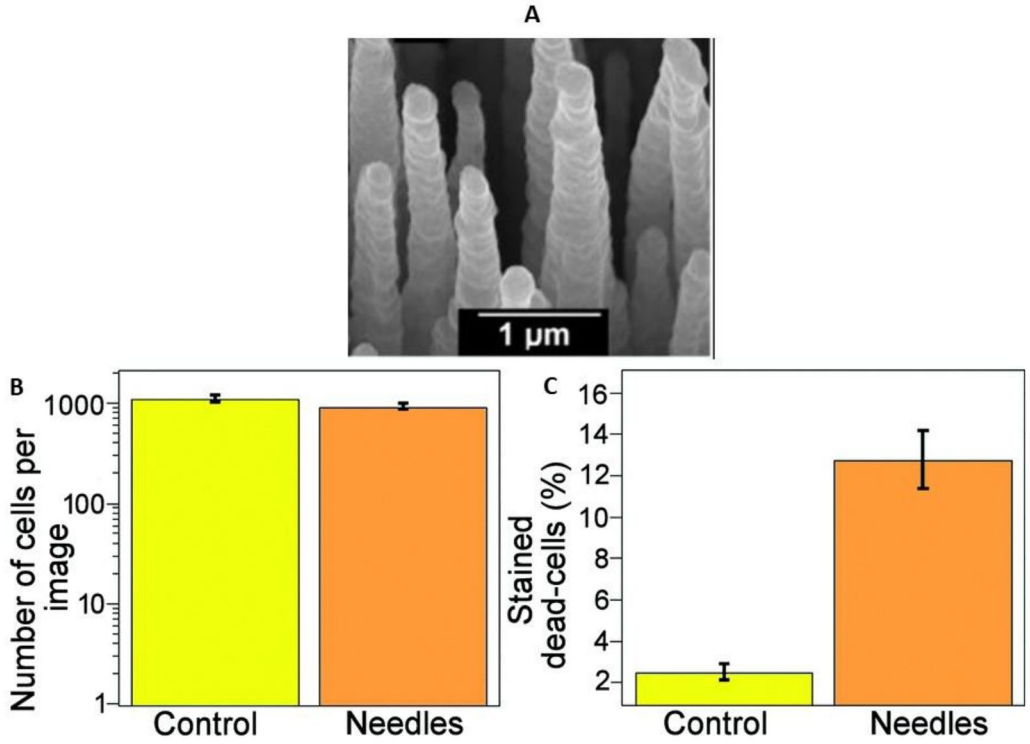

Figure 10. (A) Long needles of Black Silicon (bSi) conformally coated with boron-doped MCD. And total numbers of (B) bound bacteria and (C) percentage dead cells after 1 h incubation of P. aeruginosa on a control 'flat' BDD surface and a BDD-coated bSi short-needle surface, and subsequent viability determination by Live/Dead BacLight stain. Reproduced with permissions from [207].

adhesive properties of flat diamond films, despite the additional costs and steps required for their productions.

2.3. Influence of the roughness

Oppositely to the effect of the nanostructuration of diamond-based films, it seems that the roughness has low to no effect on the antibacterial properties. The chemical vapour deposition technique used in the most investigations to deposit the diamond based film produces films which roughness is very low (around 0.2 nm, even for high deposition rate of DLC films [246]), probably below the size of nanoprotrusion that could have a significant effect on the bacterial

adhesion or the bacterial membrane integrity. Marciano et al. investigated this parameter on their film deposited with PECVD on stainless steel. They observed a very low roughness on all their DLC films, comprised between 0.10 and 0.13 nm and verified that this parameter did not influence the bacterial growth of *E. coli*, *P. aeruginosa, S. typhimurium,* and *S. aureus* [248].

2.4. Role of the grain size on the antibacterial properties

2.4.1. Nano vs microcrystalline diamond films

The diamond film grain size, which can be tailored through different parameters [190, 283, 284], is also of interest in terms of antibacterial properties, as shown by Medina et al. They compared the antibacterial properties of two kinds of diamond films with different grain sizes against other interesting antibacterial materials such as silver, copper, stainless steel, and polyethylene. The two chosen diamond films textures are based on the grain size. The first film is composed of microcrystalline diamonds (MCD) with a grain diameter above 500 nm while the second is made of nanocrystalline diamonds (NCD) with a grain diameter below 20 nm. The size of the crystal composing the diamond film is an important parameter to be taken into account since the MCD films did not show particularly good antibacterial properties while the NCD film showed better antibacterial properties than nearly all other materials tested. NCD film was able to kill the *Pseudomonas aeruginosa* in 12 h compared to 14 h for Silver, and 48 h for the Polyethylene. Only a copper film demonstrated a better killing speed than NCD films (2 h) (Figure 11). Thanks to its higher biocompatibility than Cu, the NCD film is proven a good candidate for applications in biological media. The difference of results obtained with two different grain size can be attributed to the difference of wettability of the films (NCD films being more hydrophobic than MCD films) and the film roughness (lower NCD roughness, so less ability for the bacteria to stay attached on the film) [208]. However, it is not related to the surface termination of the film since both were terminated with –H. Additionally, the tested bacterial strain was cultivated in an organic nutrient broth which would have "mask" the film surface terminations [206].

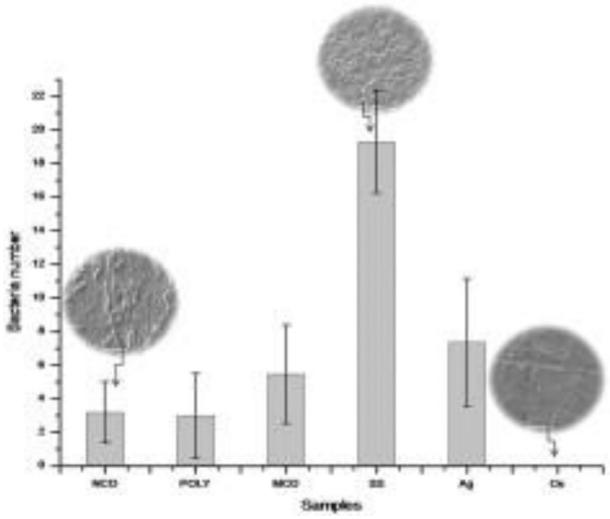

Figure 11. *P. aeruginosa* on nanocrystalline diamond (NCD), microcrystalline diamond (MCD), stainless steel (SS), silver (Ag), polyethylene (Poly) and copper (Cu) surfaces. Reproduced with permissions from [208].

2.4.2. Ultrananocrystalline diamond films performance compared to nanocrystalline diamond films

Merker et al. developed Ultrananocrystalline Diamond films, with diamond crystallite size up to 10 nm, so about twice lower than the NCD film described in the previous paragraph [210]. As it is expected with the results obtained by Medina *et al.* the crystalline size is important in the film and as observed in their study, nanocrystalline and ultrananocrystalline diamonds are too small to develop antibacterial properties [208, 210]. From these two studies, it looks like only MCD diamond films can develop antibacterial properties and that NCD and UNCD films have too small crystals to interact properly with the bacterial membrane.

2,5. Applications of antibacterial diamond and DLC materials

Different applications of antibacterial films and particles based on diamond materials are targeted by several studies. Most of them are regarding biomedical applications such as wound dressing, drug transportation or implant coatings, but additional applications in food preparation surfaces and packagings are also under the scope of research to help to feed an ever-growing number of humans on the Earth.

2.5.1. Wound dressing

Juknius et al. explored the application of Ag-DLC thin nanocomposites for their applications as smart wound dressings. Basically, the wound bandage consists of a synthetic silk fabric coated with a very thin film of Ag-DLC deposited by magnetron sputtering and stabilised with a medical-grade layer of gelatin and cellulose. The antibacterial properties are mainly expected from the silver cations released from the bandage, and they tested the silver release in aqueous media with bandages as-coated and after etching with Radio-frequency oxygen plasma during various durations. The antibacterial properties of the bandage were tested using 4 strains of *S. aureus* isolated from infected wounds in humans and animals and the bandages showing the best antibacterial properties was with an Ag-DLC coating containing 3.12 atomic percentage of silver and silver nanoparticles of

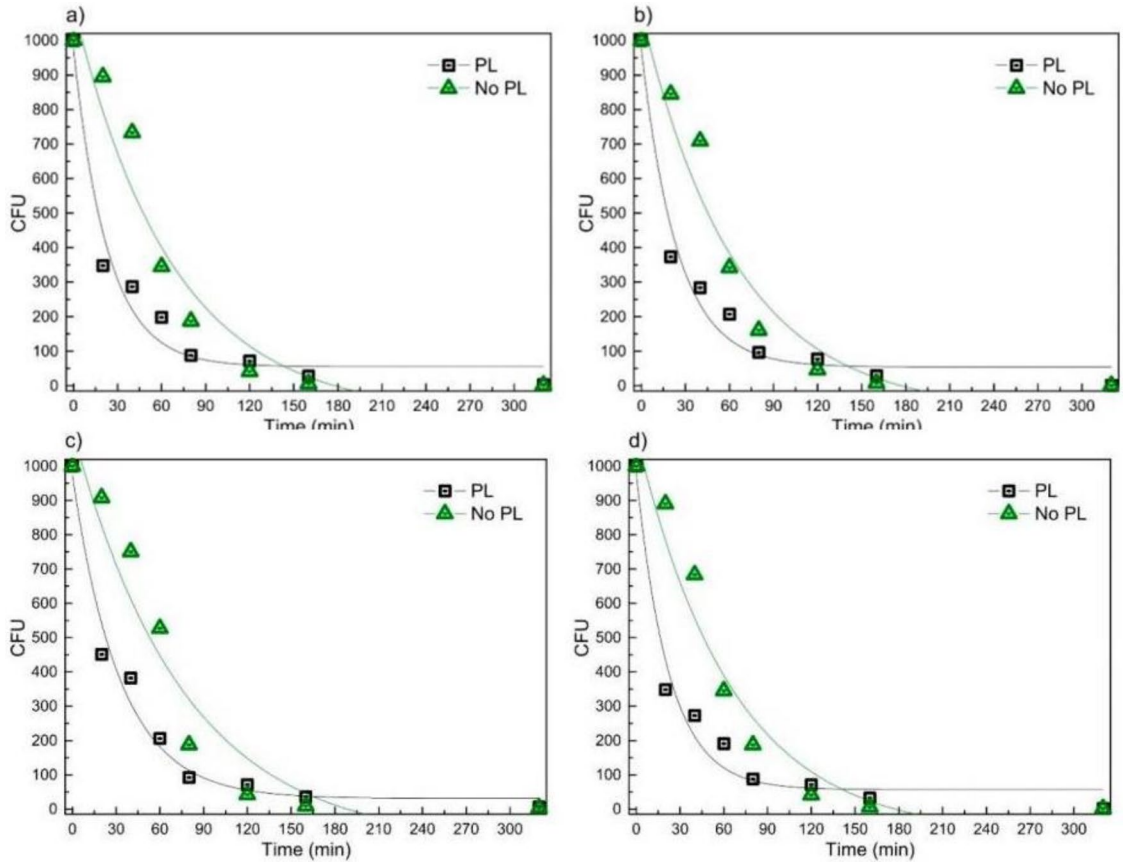

Figure 12. Time dependencies of bacteria colony forming units (CFU) versus time using the spread-plate technique for the bandage prototype (PL) and the reference sample (No PL) measured with four types of *S. aureus* bacteria strains: (a) LTSaDA01; (b) LTSaM01; (c) LTSa635 and (d) LTSa603. Reproduced with permissions from [252].

23.7 nm (Figure 12). Above stabilisation of the coating layer on top of the silk fabric, the gelatin and cellulose top layer also demonstrated positive support for the silver cation release and, thus, increased the antibacterial properties of the bandages of about 50%. Thanks to their investigation, Juknius et al. demonstrated the possibility to develop antibacterial wound dressing with a tailorable antibacterial performance depending on the bandage production and the stabilisation of the Ag-DLC coating on top of the fabric. Their results on Gram-positive bacterial strains are very promising for healing wounds without over infection and deserved more investigations on a larger number of bacterial strains isolated from wounds [252].

2.5.2. Drug transportation

The solubility in biological media, biocompatibility, and the easy-functionalisation of NDs make them a promising drug-carriers with easy transportation. Turcheniuk et al. demonstrated that they could transport ultra-volatile compounds such as essential oils while preserving their antibacterial properties against both Gram-positive and Gram-negative bacteria tested. Moreover, they also demonstrated that menthol-NDs were more efficient to avoid the biofilm formation than the antibiotic used as a positive control especially against *E. coli* even at the lowest tested concentration. Against *S. aureus*, a concentration of at least 10 µg/mL was necessary to reach the efficiency of 1 µg/mL of ampicillin. This is still a great step on the path of finding an alternative to antibiotics that are getting less efficient because of the emerging bacterial resistance. Additionally, they developed Menthol-NDs with a particle size of 15 ± 5 nm, so small enough to be used easily in biological media and excreted outside of a body and the loading of menthol onto NDs also increased by about 50 °C their thermal stability, which is far above usual biological media temperature. However, it is interesting to note that the growth of planktonic Gram-positive and Gram-negative bacteria (in other words, suspended in solution) was reduced and slowed down at all Menthol-NDs concentration in the media but not as much as the efficiency of ampicillin in solution at a concentration of 1 µg/mL for duration above 2 h. Finally, the live/dead fluorescent assay performed on both bacteria did not show dead bacteria. Consequently, Menthol-ND is not toxic to bacteria but can slow down their growth and avoid the formation of biofilms [216].

2.5.3. Biocompatible implant and surgical tools coatings

The medical implants are a widely investigated application for diamond-based antibacterial coatings because of the improvements needed in this field. A biomedical

implant needs several qualities such as hardness, low internal stress, biocompatibility for mammalian cells (or specifically human cells for human medicine) and antibacterial efficiency against nosocomial bacteria that can enter the wound and colonise the implant during the surgery or the aftercare. With a rate of implant-related infections increasing and based on Staphylococci and Streptococci biofilms colonising the surfaces of the implant, the need for efficient and biocompatible coatings for implants is increasing [285, 286].

Merker et al. investigated a coating made of a layer of silver sandwiched between two layers of UNCD, with the UNCD top layer having a variable thickness to tailor the silver release. The antibacterial properties measured are satisfactory to extend the investigations in biocompatibility and hardness and stress of the coating for implants and surgical tools. The surface being UNCD there are good chances that this coating would have good biocompatibility, but its ability to release silver cations is a concern. Moreover, their study does not contain survival assays on mammalian cells, and it would be the next step to evaluate if this coating is as promising as it looks like [210]. Another Ag-based diamond composite was investigated by Harrasser et al. They coated Polyethylene (PE) substrate with Ag-DLC coating and observed its antibacterial properties, as well as the mechanical behaviour of the Ag-DLC-PE, would be following the requirements of antibacterial implants coating (Figure 13). However, the authors underline several limits in their study. First, the potential toxicity of silver, still under discussion and investigation, is reducing dramatically the potential clinical applications of such coatings. Furthermore, only two bacterial strains were investigated in this study, which gives the first trend but is not a large enough antibacterial spectra to speculate further on bacterial strains isolated from effective implants and peri-implants infections. Finally, they didn't investigate the adhesion of human bone cells on top of the Ag-DLC-PE which is one of the main needed characteristics for implantable medical devices such as implants [256]. However, Schwarz et al. demonstrated on another Ag-DLC composite intended for implantable medical devices that the silver cations were not released in reconstituted saliva and blood fluid thanks to the surface coating with the saliva fluid proteins. This suggests that similar implantable devices with similar Ag-DLC coating wouldn't be able to release silver cations at a toxic concentration in the body and that it would still be able to kill the bacteria adhering to the proteins adhered to the antibacterial coating surface, giving a good hope for that kind of coatings at least in orthodontic implants area [258].

The development of stimuli-responsive coatings that would release antibacterial properties in a timely and punctual manner is also under the scope of research since it would increase the life of the antibacterial coating as well as reduce the amount of antibacterial compounds release in the body. It could be a good strategy to avoid the emergence of new resistance against antibacterial compounds in the future. With this in mind, Buchegger et al. developed a ZnO-DLC antibacterial composite coating that can react in the function of acidosis caused by inflammation, releasing Zn^{2+} having an antibacterial effect against the tested bacteria that are responsible for the inflammation. They demonstrated that there coating induced a Zone of Inhibition (ZOI) in agar plates which diameter is dependent on the pH: The largest one being obtained for pH = 6.4 (Figure 14). Moreover, this pH dependence is not linear since the ZOI was smaller for pH= 5.6, despite Zn^{2+} released was higher at this pH than at 6.4, suggesting other pH-related mechanisms are in place at lower pH [269].

Geyao et al. reviewed the different implants and surgical tools coatings available through the physical vapour deposition process. Among the reviewed coatings, they stated that DLC coatings are especially interesting to coat

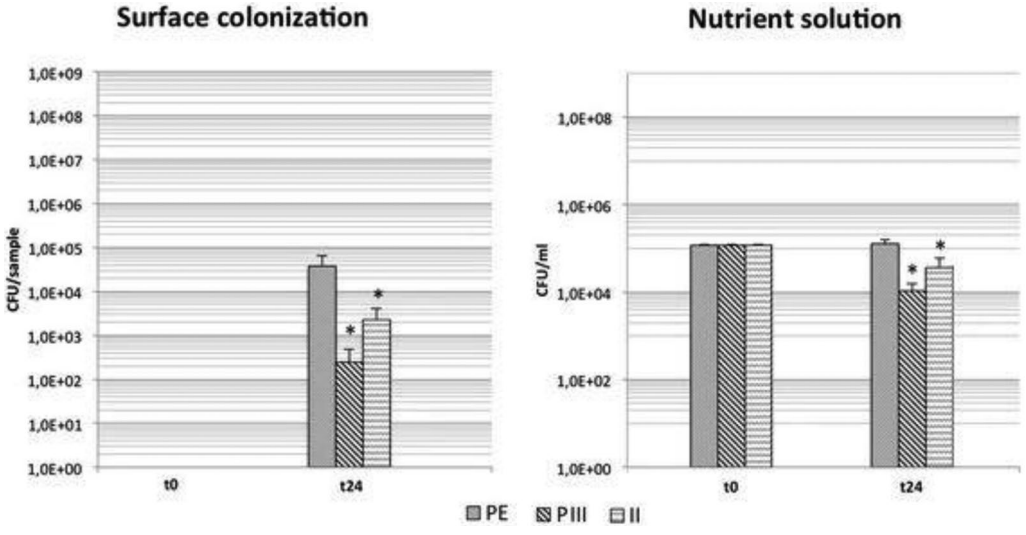

Figure 13. Bacterial growth of *S. epidermidis* in the Ag-DLC-PE testing group 2 with a comparison of different deposition methods ($t = 0$: before incubation; $t = 24$ h: after incubation; PIII: plasma immersion ion implantation; II: direct ion implantation); * = $p < .05$ (compared to untreated PE). Reproduced with permissions from [256].

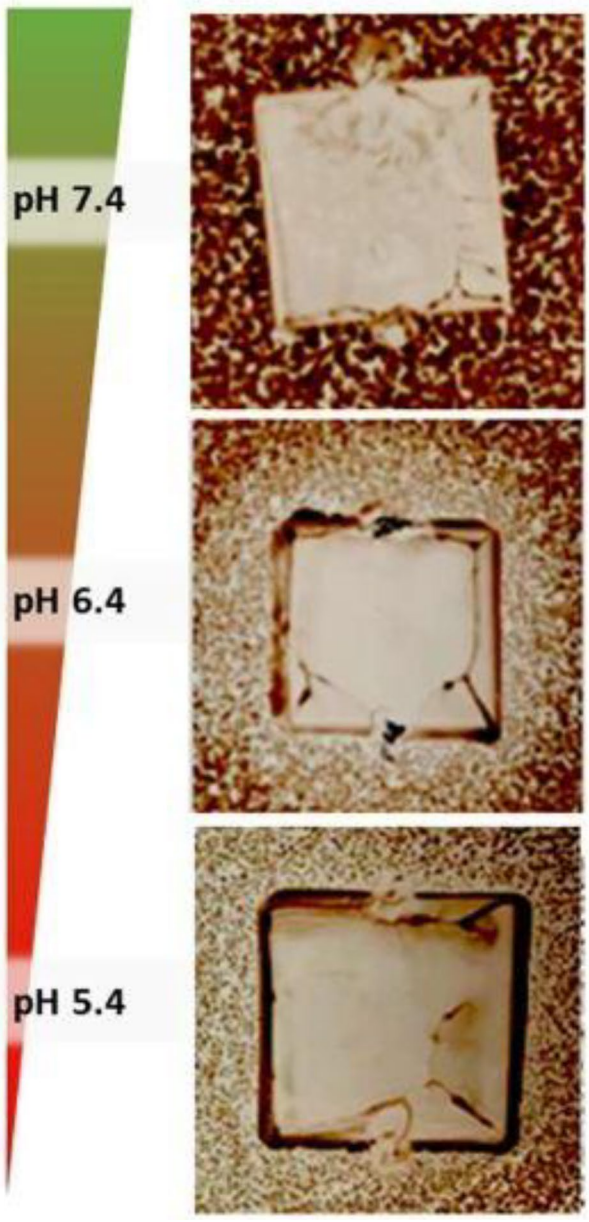

Figure 14. Antimicrobial inhibition zones of $9 \times 9\,mm^2$ DLC-ZnO-samples against Methicillin-Resistant *S. aureus* on Mueller Hinton Agar plate as a function of pH. ZOI is 9.5 mm for pH = 7.4, 13.0 mm for pH = 6.4 and 10.5 mm for pH = 5.4. Reproduced with permissions from [269].

surgical tools thanks to its ability to resist autoclaving and sterilising methods. Concerning implantable medical devices, the DLC coating is a strong ally as a transition layer between the substrate (a Titanium alloy) and the top coating (Hydroxyapatite in that case) to avoid the penetration of biological liquids/media as far as the substrate and, thus, avoid the corrosion of the substrate of the device, increasing the duration of implantable devices. Moreover, this investigated coating favours the development of human bones' cell growth *in vitro* which is a very good sign of biocompatibility. However, *in vivo* investigation are still needed to promote this coating more strongly. DLC coatings are also able to increase the mechanical and corrosion properties for Nickel and Titanium alloys, even with thin coatings (700 nm to 1000 nm). These qualities make them a good candidate for orthodontic wires and would decrease the health problem associated with the corrosion of these alloys by saliva. As a versatile biomedical coating for implantable medical devices, a DLC coating also shows an increase of biocompatibility for hips implants *in vitro* and *in vivo*, and decreases the level for the femoral head, reducing potential pain and reject for the patients. Moreover, DLC coating's low coefficient of friction makes them interesting for higher lubrication for devices such as catheters, facilitating their insertions and their removals. Geyao et al. showed in this review that DLC coatings were especially versatile for biomedical applications, and especially for implantable devices and devices in direct contact with biological media thanks to their corrosion resistance, their biocompatibility, and their low friction resistance. However, only a few of these targeted applications were already tested *in vivo* and it will require more investigation to ensure their safety and qualities *in vivo* [247].

2.5.4. Food preparation surfaces

Zakariene *et al.* investigated Ag-DLC composites on foodborne pathogens to evaluate their interest in food preparation surface coatings. The foodborne pathogens investigated were *C. jejuni* and *Listeria monocytogenes* and they used two kinds of Ag-DLC coatings: A thin coating of about 5 nm thick, and a thick coating of about 40 nm thick. Both coatings contain 22 atomic per cent of silver available for silver cations release. After 15 min contact of Ag-DLC with *C. jejuni* in the culture-based method, they realised that this coating was far more antibacterial than silver itself, which is in good adequation in terms of contact-time to avoid cross-contamination during food preparation on the surface. Additionally, they demonstrated a total cidal effect of DLC-Ag coating against *L. monocytogenes* after 24 h of contact. It confirms the addition of both DLC and silver antibacterial properties even against foodborne pathogens. However, the delay needed to kill all *L. monocytogenes* is not adequate to prevent cross-contamination for food preparation surface. Different mechanisms of action are suggested to explain the antibacterial properties of Ag-DLC against foodborne pathogens but none of them is proven yet and it is still an area to investigate deeper. Moreover, they noticed that the silver released overtime was decreasing, which would suggest an antibacterial activity limited in time. This would be a proper disadvantage for the targeted application as a surface coating for food preparation [254].

3. Conclusion

Diamond-based materials are intensively and recently investigated for antibacterial applications. As a first approach, diamond films are, by themselves, highly antibacterial, however, they are expensive to produce. DLC films only show moderate antibacterial abilities as produced and require additional functionalisation or

implantation with Silver, Copper, Fluorine, Anatase and Zinc oxides to display satisfactory antibacterial properties, despite their lower costs of production. In addition to satisfactory antibacterial properties, they also offer the creation of smart antibacterial materials such as pH-responsive antibacterial films. Several parameters are to take into account to understand diamond and diamond-related antibacterial mechanism of action and antibacterial efficiency. First, the grain size is of importance since only diamond films made of Microcrystalline Diamond displayed antibacterial properties. Second, the surface functionalisation of the films and nanodiamond is important and tailor the antibacterial properties of these materials. Finally, different applications for these materials are targeted, especially in the biomedical field, such as antibacterial wound dressings, antibacterial, biocompatible, and resistant to corrosion implant coatings, and the transportation of fragile drugs to the place of the infection. An interesting and additional field of application gaining importance with the always increasing Earth population to feed is the use of diamond-based antibacterial films for food preparation surface. However, this application especially needs improvement. As an additional benefit from the use of diamond-based antibacterial materials, several studies cited here also reported the superior antibacterial properties of these materials against antibiotic-resistant bacteria species such as Methicillin-Resistant *S. aureus* offering some hope for a future without antibiotics.

Last, but not least, carbon-based materials were also reported as efficient biosensors against the current pandemic caused by the SARS-CoV-2 virus, causing the now too well-known and deadly Covid-19 disease. Namely, Graphite-based biosensors were already able to detect the SARS-CoV-2 virus, and Graphene-based protective pieces of equipment were already developed and estimated as very efficient against the spread of this virus [287]. Because of the ability of Multi-Walled-Carbon-Nanotubes [288] and Boron-doped-diamond-based [289, 290] biosensors to detect other aerial transmitted viruses such as the Influenza virus, it is interesting to wonder their ability to detect, or even fight the Covid-19 virus.

Disclosure statement

No potential conflict of interest was reported by the authors.

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