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Review

ANTIBACTERIAL PROPERTIES OF CHITIN AND CHITOSANS

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ABSTRACT

Chitosan and chitosan based-materials are products with proved antimicrobial activity that have found many applications in medicine, pharmacy, food and textile industries. The antibacterial activity of chitosan can be explained by (i) ionic interaction of positive charges of the chitosan based-materials with negative molecules located on the surface of bacterial cells; (ii) penetration of chitosan chains into the cells and interaction with negatively charged molecules like mRNA, inhibiting protein synthesis; and (iii) realization of an external coating that chelate essential metals involved in microbial growth. Depending on the bacterial strain, all these events can take places, but with different strengths. Although there are high differences between the chemical structure of surfaces of gram-positive and gram-negative bacteria, the effectiveness of chitosans in reducing microorganism growth and multiplication seems to be similar. The antibacterial propertied of chitosan based-materials depend on molecular weight and degree of acetylation (abundance of positive charges). In general, at lower molecular weight and lower degree of acetylation the chitosans present a higher antibacterial activity. Derivatization of amino and hydroxyl groups of chitosan chains, usually provide a higher efficiency against all types of bacteria.

Keywords: chitin, chitosan, chitosan derivatives, antibacterial activity

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INTRODUCTION

Chitin, a biopolymer synthetized by crustacean [1,2], fungi [3,4], mushrooms [5,6] and insects [7], is, after cellulose, the second most abundant substance on biosphere[8]. Although chitin is synthetized by many categories of organisms, the main sources for chitin extraction are crab and shrimp shells. The difference between cellulose, that is a biopolymer made from D-glucose units linked via β (1→4) bonds, and chitin is that the units in chitin is N-acetyl-glucosamine (more exactly 2 – acetamide – 2 deoxy – D – glucopyronose) linked by β (1→4) bonds [9] (Figure 1). In fact, not all the units in natural chitins are N-acetyl-glucosamine, some of these units are deacetylated. Chitosan is obtained by deacetylation of chitin, either in alkaline conditions (chemical deacetylation in concentrated NaOH) using chitin deacetylase (enzymatic deacetylation) [10]. When the ratio of acetylated units ((1 → 4)-2-acetamide-2-deoxy-β-D-glucan versus (1 → 4)-2-amine-2-deoxy-β-D-glucan)) is higher than 40% the product is considered to be chitin, but when the acetylated units decrease under 40%, the polymer is named chitosan [11]. Chitin can be extracted from producing organisms by chemical methods (demineralization with strong acids and deproteinization with strong bases)[12] and biological (enzymatic) methods [10].

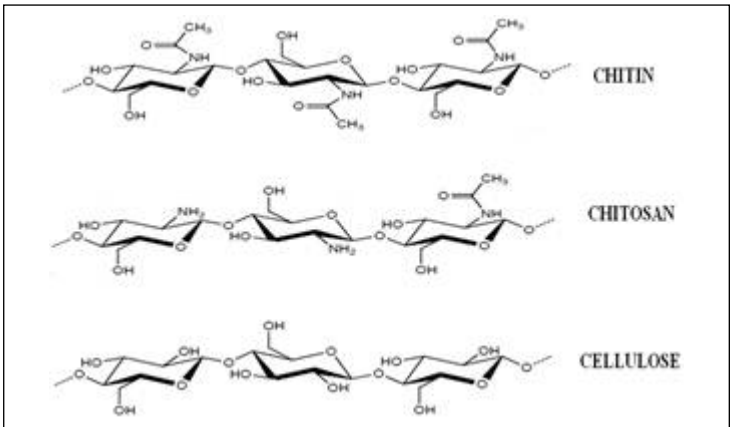

Figure 1. Chemical structures of chitin, chitosan and cellulose

Extracted chitin has a highly ordered crystalline structure, poor solubility and a relatively low reactivity. Chitosan, at least in acidic media (solution below its pKa ≈ 6.3), is more soluble than chitin and, for this reason, preferred for use as starting material in various types of applications. The solubility of chitosan varies on biological origin, molecular weight and degree of acetylation [13]. As in other cases of natural biopolymers, the characterization of chitin and chitosan is not standardized. In majority of the cases when chitosan based materials are used, the product is characterized by its molecular weight (MS)

and degree of acetylation (DA). Although there are not standards to categorize the chitosan based materials, it is accepted to be considered as low molecular weight (LMW) when the polymer has a molecular weight smaller than 50 kDa, medium (MMW), between 50 and 150 kDa and high molecular weight (HMW) when the molecular weight is higher than 150 kDa [11].

It is thought that microbes, like bacteria, fungi and parasites, being the major cause of infectious diseases, kill more peoples than other malady [14]. The compounds that kill or inhibit the growth of microbes are called antimicrobial agents. Among them, the study of antimicrobial polymers have conduct to many industrial applications, like stimuli-responsive polymeric materials for human health applications [15], antimicrobial polymers for anti-biofilm medical devices [16], antimicrobial peptides and enzymes [17,18], antimicrobial polymers with metal nanoparticles [19]. Compared with antimicrobial agents that are small molecules, the antimicrobial polymers seems to have superior efficacy, reduced toxicity, lower impact on environment and are less prone to decrease their efficacy due to development of microbial resistance [20].

In order to adhere to a substrate, the microbes excrete extracellular polymeric substances that form a matrix where the cells can better develop themselves. This matrix, also called biofilm is a polymeric conglomeration composed of polysaccharides, proteins and nucleic acids [21]. Destruction or malfunction of these biofilms is one of the major target of antibacterial strategies [16]. For instance, antimicrobial peptides can disrupt the bacterial cell membrane [18]. Inhibition of biofilm formation is a hopeful strategic alternative to killing microbes, as inside the matrix, bacteria are better protected than in solution free state [22].

Chitosans are largely used as antibacterial agents [23]. The degree of acetylation and the molecular weight have a major role in the antibacterial activity of chitosan based products. In order to increase its low solubility the raw chitosan is chemically modified either at its primary amino or at the primary alcohol groups [24]. Due to incomplete characterization of chitosan-based materials, it is rather complicate to compare them and to control the influence of various types of factors that affect the antibacterial activity and mode of action of chitosans. Even the activity of chitosan was investigated as antimicrobial agent against a large range of organisms, like bacteria, yeasts, fungi or algae, in experiments involving in vitro or in vivo interactions, it is not yet clear if chitosan has a bacteriocidal (kills the live bacteria) or bacteriostatic (obstructs the growth of bacteria) activity [11]. Only recently there were made some attempts to introduce some rules and limits in classification of chitosan samples according to the molecular weight and the degree of deacetylation [23].

Apart the influence of MW and DA of chitosan samples, which has to be characterized with precision in order to can compare the antibacterial effect (like minimal inhibitory concentration MIC), other factors like pH, temperature, salinity can play a significant role in the antibacterial activity. Due to chitosan solubility at lower pH values, chitosan based products have a higher antibacterial activity in acidic environment [25]. The experiments have proved that, in most of the cases, the antibacterial activity of chitosans is increased at higher temperature values (until 40°C) and lower pH values (between 4 and 6) [23,26].

Probably due to solubility issues, it seems that the molecular weight (MW) of chitosans has a greater influence on antibacterial activity than the degree of acetylation (DA). Studies on *Bacillus cereus, E. coli, Staphylococcus aureus, Pseudomonas aeruginosa, Salmonella*

enterica, B. subtilis, Listeria monocytogenes and *Klebsiella pneumoniae* have shown that the chitosans with smaller MW have a higher antibacterial activity, as small polymers have higher mobility and stronger interactions with the bacterial walls, than the chitosans with high molecular weights [11]. Studies on some Gram-positive and Gram-negative bacteria have revealed that antibacterial activity is higher at lower DA [10].

PASSIVE OR ACTIVE ACTION

Passive Action

Antibacterial polymers, like chitosan, can act as antibacterial agent passively, i.e. can reduce protein adsorption on its surface that conducts to impairing the adhesion of bacteria. That means that these polymers do not kill bacteria but repel them. Repelling process can be realized by (1) hydrophilic / hydrophobic repulsion; (2) electrostatic repulsion, or (3) to have a low surface free energy [27]. For example, poly(ethylene glycol) was used as neutral polymer brush system to prevent protein and cell adhesion against *Staphylococcus aureus, Escherichia coli* and *Pseudomonas aeruginosa* [28] and charged polyampholytes, like phosphobetaine and phospholipid polymers were used against *Staphylococcus aureus*[29]. Use of albumin-glycerol and whey-glycerol no cell growth was observed in the case of *Bacillus subtilis* and *Escherichia coli* [30]. Polyphenols were effective against periodontal bacteria (*Streptococcus mitis, Fusobacterium nucleatum, Porphyromonas gingivalis*) reducing the film formation [31].

Active Action

In the category of active polymers are the compounds that actively kill bacteria that stick to the polymer surface, as in the case of cationic biocides, antimicrobial peptides, or antibiotics. In this case, between bacteria and polymer can be electrostatic and / or biocidal interactions [27]. For example, the polymers functionalized with positively charged quaternary ammonium groups can interact with the cell wall and cell membrane, conduction to leakage of intracellular content and cell destruction. Acrylamide polymers with quaternary ammonium have proved active action against *Staphylococcus albus, Escherichia coli, Rhizoctonia solani, Fusarium oxysporum* [32], and polyurethane containing quaternary ammonium groups were active against *Staphylococcus aureus, Escherichia coli* [33]. Combination of two active compounds, an antimicrobial cationic monomer (bearing tertiary amine) and an antioxidant and antimicrobial hydrophobic monomer has provided a synergistic action against biofilms (of *Staphylococcus epidermidis* and *Staphylococcus aureus*) and suppress reactive species oxygen [34].

Polymeric Biocides

Antimicrobial polymers can be included in the following categories: polymeric biocide, biocidal polymers and biocide-releasing polymers [35]. In the case of polymeric biocides, various types of monomers with antimicrobial activity, i.e. monomers bearing amino, carboxyl, or hydroxyl groups are linked to a polymeric matrix and used to form the final product [35]. There are situations when the final polymer is less active than the monomers, due to the fact that the polymer is less soluble than monomers and / or because the biocidal groups do not reach their target [36]. Polymerization of antibiotics (Penicillin V and Cephradine) with PEG-Lysine via a hydrolytically stable bond conducted to an inactive polymer [37]. If the active monomers were linked to the matrix via a labile bond, the conjugates exhibited full antimicrobial activity. Polymeric materials with quaternary ammonium and phosphonium salts were used with success against *Staphylococcus aureus* and *Escherichia coli* [38]. Other polymeric biocides were constructed with benzimidazole (active against *Micrococcus luteus, Staphylococcus aureus, Bacillus subtilis*), halogenated monomers (*Staphylococcus aureus* and *Escherichia coli*) or various types of quaternary ammonium groups [27].

Biocidal Polymers

In the case of biocidal polymers, the active chemical functions are part of the polymer itself. The polymers contain quaternary ammonium groups, or phosphonium, tertiary sulfonium or quanidinium groups that interact with the negative charged groups from the outer membrane of the bacteria. Due to their membrane proteins, teichoic acids of Gram-positive bacteria, and negatively charged phospholipids at the outer membrane of Gram-negative bacteria, the cationic polymers can lead to destabilization of cell surface and induce the bacterial death. The effectiveness of these cationic polymers is in direct relation with the charge density of the cationic function on the polymeric backbone [27,39].

There are many type of biocidal polymers: quaternary ammonium polyethyleneimine, quaternary phosphonium modified epoxidized natural rubber, arginine – tryptophan rich peptide, guanylated polymethacrylate, ammonium ethyl methacrylate, metallo-terpyridine carboxymethyl cellulose, poly(*n*-vinylimidazole) modified silicone rubber, heparin, poly-ε-lysine, and gramicidin A, chitosan and others [27]. Among them chitosan, due to its nontoxicity, biodegradability and biocompatibility, is the most common natural biocidal polymer exhibiting inherent antimicrobial activity. Other group of very common biocidal polymers comprise antimicrobial peptides. More than 1000 peptides have been screened for antimicrobial activity. These polymers, beside disrupting the bacterial membranes and inhibiting the cellular processes, act as immunomodulatory agents stimulating the noninflammatory host immune response [40]. The unwanted side effects of antimicrobial peptides include antimicrobial resistance, low stability and high production costs [27].

Biocide-Releasing Polymers

In the category of biocide-releasing polymers, the products are realized by polymerization of biocide molecules together with the polymeric backbone or by creation of composites between polymer and biocide molecules. In fact, in biocide-releasing polymers the polymer itself is a carrier for biocides molecules, and the product in its polymeric form exhibit antibacterial activity due to incorporation of antibiotic or antiseptic compounds. The

controlled release of biocidal molecules from the polymer has the advantage of releasing of active molecules that have in vivo short half-lives for a certain time, maintaining in this way a high local biocide concentration in the vicinity of bacteria [27]. Example of such biocide-releasing polymers are dextran containing gentamicin [41], poly-L-lysine, polyethylene glycol containing staphylolytic LysK enzyme [42], poly(octanediol-co-citrate) having choline chloride, tetraethylammonium bromide, hexadecyltrimethylammonium bromide, methyltriphenylphosphonium bromide, cyclodextrin with triclosan, poly(methyl methacrylate) with silver [43], or polycaprolactone with silver [44].

The antimicrobial polymers can be classified also in surface-bound or solution-base polymers categories. While surface-bound polymers have direct antimicrobial activity on the polymer surface, the solution-based polymers should be dissolved or dispersed in solution in order to manifest antimicrobial properties. Most of the biocidal polymers enter in the surface-bound polymers category, while biocide-releasing polymers should be solubilized in order to release the biocidal molecules. Polymeric biocides may be categorized in both categories, surface-bound or solution-base polymers, depending of the chemical structure of bioactive repeating units [27].

THE ANTIMICROBIAL MODELS OF CHITOSAN

The fact that there are some evidences that the leakage of intracellular components produced by chitosan in gram-negative bacteria is superior to that produce in gram-positive bacteria can be explained by the difference in composition of membranes and walls of these groups of bacteria, i.e. the outer membranes of gram-negative bacteria contain mainly lipopolysaccharides with phosphate and pyrophosphate groups that make a higher density of negative charges on bacterial surface comparing with gram-positive bacterial cells, where the membranes are composed by peptidoglycans associated to polysaccharides and teichoic acids. On the other hand, there are publications where the antibacterial effects of chitosans are stronger on gram-positive bacteria (*Listeria monocytogenes, Bacillus megaterium, B. cereus, Staphylococcus aureus, Lactobacillus plantarum, L. brevis, L. bulgaris*, etc.) than on gram-negative bacteria (*E. coli, Pseudomonas fluorescens, Salmonella typhymurium, Vibrio parahaemolyticus*, etc.) [11]. This would suggest that the antibacterial mode of action of chitosan is dependent upon the host microorganism [45].

Another mechanism of chitosan antimicrobial activity is the property of chitosan to bind metals, i.e. the amine groups has the capacity to uptake the metal cations by chelation [46]. Contrary to the situation when chitosan acts at low pH with the negative charges from the bacterial cell surface, the chelation process is more efficient at high pH, when the positive metal ions can bound to chitosan, to unprotonated amino groups and the electron pair on the amine nitrogen is available for donation to metal ions. At pH lower than 6, the metal can interact with only one amino group and three hydroxyls or water molecules. At pH between 6 and 7 the metal ion can interacts with two amino groups from two different chains. When the pH is higher than 7, the predominant complexation is ruled by two amino and two hydroxyl deprotonated groups. In the process of chelation of metal ions by chitosan, it is possible to be involved some essential nutrients for bacterial cells, that being extracted from their normal sites, contribute to cell death. Although possible, the metal chelation

mechanism seems to have a reduced influence to the overall antibacterial activity of chitosans [11].

Another possible mechanism of action of chitosan against bacteria is its binding with microbial DNA and / or mRNA, interfering with transcription and translation processes [47], although not all the authors agree with this possibility [48]. The dominant argument is that chitosan acts principally as an external membrane disruptor rather than as a penetration material [11].

SENSITIVITY OF MICROORGANISM STRAINS TO CHITOSAN

There are numerous reports about the minimum inhibitory concentration (MIC) for chitin, chitosan, their derivatives or combination, with diverse results for different microorganisms. MIC is defined as the smallest concentration of an antimicrobial that will inhibit the observable development of a microorganism after overnight cultivation. Unfortunately, the non-standardized protocols make difficult to compare MIC results from different authors. For example, MIC of chitosan for *Escherichia coli* vary from 20 [49] to 1000 ppm [50], for *Vibrio parahaemolyticus* from 150 [51] to 1000 ppm [52] and for *Staphylococcus aureus* from 20 [49] to 1250 ppm [53].

Gram-positive bacteria

The explanation of the antibacterial effect of chitosan on gram-positive bacteria is the non-covalent binding of chitosan to teichoic acid incorporated in the peptidoglycan layer [54]. The surface localized teichoic acid molecules are important for cell division and interaction with chitosan can impair this process and possible other processes equally important for the bacterial growth. The roles of teichoic acids are to protect the cells against environmental stress, to control the enzyme activity and to assure a cationic concentration of the cell surface to facilitate the binding of the cell to receptors. The significance of teichoic acid towards chitosan action was shown on *S. aureus* mutants in genes involved in teichoic acids biosynthesis. The mutant species of *S. aureus* were more resilient compared to the wild type. This proves that polyanionic teichoic acids are the target site of chitosan antibacterial activity towards gram-positive bacteria. At least in the case of small molecules of chitosan (smaller than 5 kDa) it was advocated that the polymer can enter in the bacterial cell and block the synthesis of DNA [55], emphasizing the fact that the molecular weight of chitosan is an important factor that can affect the mode of action of this polymer [23].

There are articles describing the antibacterial activity of chitosan in the form of nanoparticles. At least for S. aureus, the nanoparticles of chitosan proved to have a lower bactericidal concentration (4 μg/mL) compared to soluble chitosan (32 μg/mL). The antimicrobial activity is improved when chitosan nanoparticles are loaded with cupper (2 μg/mL) [56].

There are reported cases when chitosan films have not antimicrobial activity, at least against *Staphylococcus aureus* and *Staphylococcus epidermidis*, although the chitosan

solutions were very effective as an antimicrobial agent [57]. Against other types of bacteria (like *Lactobacillus plantarum* and *Listeria monocytogenes*) chitosan films proved to be active [23]. In the form of films from quaternary chitosan, the antibacterial properties are manifested even toward *Staphylococcus sp*. cells [58].

Gram-negative bacteria

One mechanism that is believed to be involved in the interaction of chitosan with gram-negative bacteria is correlated to the chelation effect of chitosan with cations when the pH is above pKa [59]. Another mechanism of action of chitosan is the electrostatic interaction of chitosan with anionic parts of lipopolysaccharides from the outer membrane of gram-negative bacteria [11]. It is also possible that chitosan (at least polymers with low molecular weight) pass through membrane and interferes with DNA/RNA synthesis [55]. Which of these mechanisms is prevailing remains unclear. Taking into account the difference in MW of the chitosan-based products, it appears that oligo-chitosan have a lower antibacterial activity than low, medium and high MW chitosans [23]. In fact, the differences in antibacterial activities of different chitosans, with different MW is rather small and seems to be largely dependent on the bacteria.

Considering the fact that it was observed a higher antimicrobial activity with increasing the degree of deacetylation, electrostatic interactions could be the major factor determining the antibacterial activity of chitosans. Chitosan (pKa6.3–6.5) has the highest antibacterial activity at low pH due to the protonated amino groups. This explains why quaternized chitosan derivatives are more effective than chitosan and why chitosan is more effective than chitin. Quaternized chitosan derivatives have a better solubility than chitin and raw chitosan and an improved antibacterial activity, due to permanent positive charges [60].

Other non-covalent interactions between chitosan and molecules from the bacterial surface can be considered to explain the mechanism of chitosan antibacterial activity. For example, chitosan can interact with cholesterol molecules and destabilize the bacterial membrane [61].

N-SUBSTITUTED CHITOSAN DERIVATIVES

Although it was confirmed that chitin and raw chitosan have antibacterial activities, the use of these polymers is limited due their low solubility in aqueous solutions. Water soluble chitosan based materials can be realized by introduction of stable positive charges in the polymer chains. The resulted cationic polyelectrolyte derivative presents antibacterial properties that are independent of the pH of the environment. Quaternization of the nitrogen atoms of the amino groups of raw chitosan is one possibility to obtain soluble derivative of chitosan. This can be realized by extensive methylation (with dimethylsulfate in strong alkaline environment) conducting to N,N,N-trimethylchitosan derivative [62].

Reports with quaternary salts of chitosan shown that the antibacterial activity is higher than that of raw chitosan [63]. For example, the activity of N-propyl-N,N-dimethyl chitosan

against *E. coli* is 20 times higher then that of raw chitosan proving the importance of cationic permanent charges for the antibacterial activity [64]. An important characteristic of the chitosan derivatives is the data that the alkyl moiety have an significant role in the antimicrobial activity, promoting hydrophobic interactions with hydrophobic residues from the bacterial membrane. That means between chitosan derivatives and molecules from the bacterial surface can take place hydrophobic and hydrophilic interactions, favoring the structural affinity between the bacteria cell wall and the polymer derivative [11]. This was confirmed by the works of Rabea [65] that confirmed that antimicrobial activity increases with the chain length of the alkyl substituent. Hydroxypropyl and carboxymethyl chitosans derivatives have also antibacterial activities. Hydroxypropyl chitosans, grafted with maleic acid are soluble derivatives of chitosan and at neutral pH present an antibacterial activity higher than that of raw chitosan [66]. Although carboxymethyl chitosan derivatives can have both negative and positive substituent groups, it seems that the influence of carboxymethyl part is less important than the presence of positive charges on the polymer chain, or its molecular weight [11]. Other types of chitosan derivatives have also shown improved antibacterial activities. For example, acyl thiourea chitosan derivatives have higher antimicrobial activity against *S. aureus* and *Sarcina sp*. [67]. Similarly, thymine-chitosan [68], sulfonated chitosan [69] and alkyl sulfonated chitosan [70] showed a superior antimicrobial activity against *S. aureus*.

N,O-SUBSTITUTED CHITOSAN DERIVATIVES

Diverse thiosemicarbazone chitosans [67] and hydroxylbenzene-sulfonanilide chitosan derivatives have shown antimicrobial activities against *S. aureus* and *Sarcina sp*., while quaternary carboxymethyl chitosan derivatives have presented antibacterial activity against *B. subtilis* and *S. pneumonia* [71]. Quaternary chitosan derivatives showed antibacterial activity against *E. coli* with MIC values ranging between 0.006 till 0.3 mg/mL [72]. 2-Hydroxypropyl dimethyl-benzyl-ammonium N,O-(2-carboxyethyl) chitosan chloride with a varying degree of quaternization showed an increased antibacterial activity against *S. aureus* [73].

APPLICATIONS OF POLYMERS WITH ANTIBACTERIAL PROPERTIES

Medical Industry

Medical industry is one of the major beneficiary of any kind of materials that present antibacterial activity. The surface of any kind of medical instruments is susceptible to microbial infection. Although there are notable progresses in materials and procedures, most hospital-acquired infections derive from medical devices. To diminish biofilm development and to increase the long-term use of medical devices a coating copolymer of 4-vinyl-n-hexylpyridinium bromide (VP) and dimethyl(2-methacryloyloxyethyl) phosphonate

(DMMEP) active against several pathogenic bacteria (*Staphylococcus aureus, Staphylococcus epidermidis, Streptococcus sanguinis, Escherichia coli*) was proposed [74].

Antimicrobial peptides, that are also involved in modulation of the immune response [75], antimicrobial wound-dressing containing antimicrobial peptides grafted to chitosan (polycationic polymer) or to alginate (polyanionic polymer) presented a high antimicrobial effect (in the range of 4–6 log reduction) for *Staphylococcus aureus* and *Klebsiella pneumonia* [76] with no toxic effect against human dermal fibroblasts [27].

Composite gels based on chitosan and ZnO, containing gentamicin that was slowly released under planktonic and surface-attached conditions have shown highly effective antimicrobial activities against Pseudomonas aeruginosa and Staphylococcus aureus [77]. The system has the advantages to be transferred to any other soluble antibiotic or any other type of drugs as the active molecules remain trapped in the chitosan-ZnO composite gel, and, most important, when used in a wound dressing device, it maintained a moist environment to the wound.

Impregnated catheters with triclosan, rifampicin and sparfloxacin have shown to be active against *Proteus mirabilis, Escherichia coli* and *Staphylococcus aureus*, providing a solution to reduce catheter-associated urinary tract infection in both short-term and long-term urinary catheter use. The active chemicals were released from the polymeric coating of catheters during several weeks, preventing colonization of wound and catheters with bacteria [78].

Food Industry

Another industry that can benefit from the use of antimicrobial polymers is food industry. Here, the major application of polymers with antibacterial properties is realization of packages that prevent the development of microbial cells. Because of its favorable properties of negligible human toxicity and antibacterial effectiveness, nisin was approved to be used as a food preservative. Nisin was impregnated in films created from chitosan – poly-lactic acid, from where was slowly released during the period of validity of food products. These films have shown to have a high antimicrobial activity against *Staphylococcus aureus* [79].

Chitosan based products were used to enhance fish preservation during storage [80], to improve the quality of fresh cut broccoli [81] or to control bacterial contamination during brewing [82]. Another advantage of using chitosan based-product in food packages is the fact that it was noticed an improvement in the sensory quality during storage. This was observed for packages of chicken meat [83], of cherry tomato fruits [84], jujube fruits [85] or red table grapes [86].

Textile Industry

Another industry that benefits from development of antibacterial polymers is textile industry. Under suitable conditions of temperature and humidity, cloths are good substrates

for microbial growth. Nanocomposite coatings with high thermal stability and high antimicrobial activity, based on Ag:ZnO/chitosan were developed using a modified sol-gel method with 3-glycidyloxypropyltrimethoxysilane and tetraethoxysilane as functionalization agents and were applied to make antimicrobial fabrics from textile blend of cotton/polyester (50%/50%) [87]. Silk coated with chitosan showed an antibacterial activity [88]. When chitosan was mixed with dyes, beside an improved antimicrobial activity it was observed and improved dye-ability of silk [89].

4. CONCLUSIONS

Chitosan is a chitin derived biopolymer with many interesting applications. Many of its applications in medicine, pharmacy, textile or food industries derive from antibacterial activities of chitosan based-materials. The effectiveness of antimicrobial properties can be modulated by selecting the range of molecular weight of the polymeric chains and the degree of acetylation of amino groups. Further improvement of antibacterial efficiency of chitosan based-materials can be realized by derivatization of amino and / or hydroxyl groups of monomeric units of the polymeric chain. Depending on the application, chitosan based-materials can be presented in the soluble form, films or nanoparticles dispersed in a suitable environment. Having so many parameters that can be modified, one can produce chitosan based-materials with antibacterial activities against gram-positive and gram-negative bacteria.

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