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Review

The newest achievements in synthesis, immobilization and practical applications of antibacterial nanoparticles

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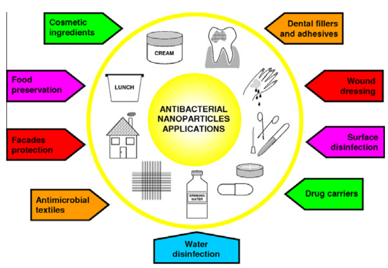
HIGHLIGHTS

- Synthesis and immoblization of antibacterial nanoparticles.
- The mechanism of nanoparticles antibacterial activity.
- Antibacterial nanoparticles for practical applications.
- Novel nanomaterials for medical sciences, water treatment and surface protection.

GRAPHICAL ABSTRACT

The versatility of antibacterial nanoparticles applications.



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ABSTRACT

Nanotechnology is emerging as a new interdisciplinary field combining biology, chemistry, physics and material science. The review describes recent developments in the synthesis, modification and practical applications of nanoparticles (NPs). Moreover, this work describes the methods of NPs incorporation in various matrices. Taking advantages of the specific characteristics of NPs such as high surface to volume ratio, homogeneous particles size distribution, possibility of facile surface modification, good stability, and the ease of preparation, these materials offer new solutions in the fields of pharmacy, dentistry, medicine, biology, and material science. Size, shape, size distribution and surface decoration of NPs are the key factors determining their specific properties. Due to the strong antibacterial properties and low toxicity towards mammalian cells of some NPs they have been successfully applied in a wide range of areas including wound dressing, protective clothing, new nanomedicines, antibacterial surfaces, water treatment, food preservation, and cosmetics as biocidal and disinfecting agents. Suggested mechanism of NPs antibacterial activity is also presented.

Abbreviations: BTCA, 1,2,3,4-butantetracarboxylic acid; CPt NPs, colloidal platinum nanoparticles; CTAB, cetyltrimethylammonium bromide; DMF, *N,N*-dimethylformamide; DNA, deoxyribonucleic acid; EG, ethylene glycol; GO, graphene oxide; MBC, minimum bactericidal concentration; MIC, minimum inhibitory concentration; MRSA, methicillin resistant *Staphylococcus aureus*; MTEOS, methyltriethoxysilane; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; NPs, nanoparticles; NTs, nanotubes; OAc, acetate; PAA, poly(acrylic) acid; PEG, poly(ethylene) glycol; PES, polyethersulfone; PLGA, poly-(D,L-lactide-co-glycolide); PTBAM, poly[2-(*tert*-butylaminoethyl) methacrylate]; PVDF, poly(vinylidene fluoride); PVP, poly(vinylpyrrolidone); QA-PEI, quaternary ammonium polyethyleneimine; QDs, quantum dots; ROS, reactive oxygen species; SDS, sodium dodecyl sulfate; SLN, solid lipid nanoparticles; SPES, sulfonated polyethersulfone; STEM–EELS, scanning transmission electron microscopy–electron energy-loss spectroscopy; TBAB, tetrabutylammonium bromide; TCP, tricalcium phosphate; THF, tetrahydrofuran; VRSA, vancomycin resistant *Staphylococcus aureus*.

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Contents

1. Introduction

Nanotechnology is an interesting branch of science offering materials exhibiting structural features between those of atoms and bulk materials with at least one dimension in the nano range [1]. Nanomaterials have been already applied in many fields of human life. In the group of nanomaterials carbon nanotubes [2], fluorescent nanocrystals [3], nanoporous silica [4], dendrimers [5], liposomes [6], graphene [7], and nanoparticles [8] can be listed. There is a growing interest in the use of nanomaterials in biosciences. The increasing nanomaterials application in this field follows from their unique properties. As an example ordered nanoporous materials exhibiting high surface area and uniform pore size distribution were proposed as the carriers for various active substances in drug delivery systems [9,10] while semiconductor nanocrystals characterized by high photostability and bright photoluminescence called quantum dots (QDs) have been applied as efficient fluorescent probes for bioimaging of cancer cells as an alternative to traditional organic fluorophores [11,12]. Moreover, nanomaterials offer a great potential in adsorption and degradation of environmental pollutants as they exhibit catalytic and photocatalytic activity [13].

Over the past few years there has been a tremendous growth of research activities to explore properties of nano-sized particles. Nanoparticles may occur in different shapes such as spheres, platelets [8,14], nanorods [14,15], dimeric nanorods, hexagonal discs, P-shaped [15], U-shaped [16], nanoflowers [17], and nanobars [18]. Nano-sized organic and inorganic particles have been extensively studied across the fields of photochemistry [19], electrochemistry as the element of batteries [20] and supercapacitors [21], electrocatalysis [22], and heterogeneous catalysis [23]. In recent years, metal and metal oxide nanoparticles based on silver [24,25], gold [26], copper [27], copper oxide [28], zinc oxide [29], maghemite [30,31], and magnetite [32] have been also applied in medicine, dentistry, pharmacy, and biology. Other types of nanoparticles have arouse also a special attention in biomedical research field. Zeolite nanoparticles incorporated in polyamide film membranes markedly improved its performance for forward osmosis [33], while carbon black nanoparticles have been used for the real time drug delivery investigation [34].

With increasing concerns of bacterial infections, there is a growing need to develop new and powerful antibacterial agents. Particularly, nanoparticles have been applied in food preservation [8], burn dressings [35], safe cosmetics [36], medical devices [37], water treatment [38], and other range of products [39–43] what is schematically presented in Fig. 1. The wide nanoparticles bioapplication is due to their excellent antibacterial activity on several gram positive and negative bacteria [44]. It has been demonstrated that the bactericidal effect of nanoparticles depends on their size, shape, size distribution, morphology, surface functionalization, and their stability. Additionally, the use of inorganic nanoparticles as antimicrobial agents has several benefits such as improved stability and safety in comparison with the organic antimicrobial agents [45]. Antibacterial nanoparticles can be composed of metals [42], metal oxides [46], metal salts [47,48], metal hydroxides [49], organic nanocarriers loaded with antibacterial agents [50], hybrid materials [51] and polymers exhibiting antibacterial properties [52]. The thorough classification of antibacterial nanoparticles based on aforementioned examples and recent literature [8,39,53–65] is demonstrated in Fig. 2.

Nanoparticles can be synthesized by chemical, physical and biological methods. However, chemical reduction methods are the most commonly used. Recently, biosynthesis with the aid of novel, non-toxic, eco-friendly, and convenient biological materials namely fungi [55], bacteria [66], biomolecules [67], and plant extracts [68] is under much investigation.

The antimicrobial activity of synthesized nanomaterials is usually evaluated quantitatively or qualitatively [56] against model organisms by calculation of the minimum inhibitory concentration (MIC) [69], minimum bactericidal concentration (MBC) [70], disc diffusion method [51,56,57], growth inhibition method [50], colony-counting procedure [50], halo test [71], agar [61,65] or broth [50] dilution technique, turbidity assay [72] or microdilution method [73]. The antibacterial activity of nanoparticles is usually estimated on the representative group of pathogenic microorganisms such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Listeria monocytogenes*, and *Streptococcus mutans*. These bacteria are responsible for various infections in humans of reduced immunity and represent a major threat to public health in food packaging [8], synthetic textiles [41], medical devices [37],