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Review

Copper-polymer nanocomposites: An excellent and cost-effective biocide for use on antibacterial surfaces

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ABSTRACT

The development of polymer nanocomposites with antimicrobial properties has been a key factor for controlling or inhibiting the growth of microorganisms and preventing foodborne diseases and nosocomial infections. Commercially available antibacterial products based on silver-polymer are the most widely used despite the fact that copper is considerably less expensive. The incorporation of copper nanoparticles as antibacterial agents in polymeric matrices to generate copper-polymer nanocomposites have presented excellent results in inhibiting the growth of a broad spectrum of microorganisms. The potential applications in food packaging, medical devices, textiles and pharmaceuticals and water treatment have generated an increasing number of investigations on preparing copper based nanocomposites and alternative polymeric matrices, as potential hosts of nano-modifiers. This review presents a comprehensive compilation of previous published work on the subject, mainly related to the antimicrobial activity of copper polymer nanocomposites. Within all the phenomenology associated to antibacterial effects we highlight the possible mechanisms of action. We discuss the differences in the susceptibility of Gram negative and positive bacteria to the antibacterial activity of nanocomposites, and influencing factors. As well, the main applications of copper polymer-metal nanocomposites are described, considering their physical and chemical characteristics. Finally, some commercially available copper-polymer nanocomposites are described.

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1. General background

The incorporation of metal nanoparticles in a polymer matrix generates new materials called nanocomposites. The combination of the different properties of these components (polymer and nanoparticles) can render a material with improved optical, electronic, mechanical and antimicrobial properties. Nanocomposites with antibacterial properties can be obtained either by incorporating nanoparticles with known antibacterial activity, or by enhancing the antibacterial properties that the polymeric matrix already has. In the latter case the substantial enhancement of biocidal capacity has been associated with a synergistic effect of the two components present in the composite. Therefore, the polymer not only provides a supporting matrix for nanoparticles, but can also enhance antibacterial performance and extend the possible applications of this material to meet several requirements in the biomedical field, water treatment, and food industry, among others.

There is an urgent need to develop materials that can control or prevent microbial colonization due to emerging infectious diseases that are affecting global economies and public health. Medical devices such as, endotracheal tubes, vascular and urinary catheters, and hip and knee prosthetics are responsible for over half the nosocomial infections in the United States [1]. These and other medical devices are made from polymeric materials [2]. The longer a nosocomial pathogen persists on the surface of a material, the longer it exists as a source of transmission and thus endangers susceptible patients or health workers [3]. The treatment of infections associated with medical devices can be difficult and expensive. In 2011, 1 in 25 hospital patients in the United States had at least one health care-associated infection (HAIs). Out of an estimated 722,000 cases, 75,000 patients died during hospitalization [4]. Central line-associated bloodstream infections were the most costly HAIs, followed by ventilator-associated pneumonia, surgical site infections, clostridium difficile infection, and catheter associated urinary tract infections. The total annual cost for these 5 major infections is $9.8 billion dollars [5].

In the food industry, pathogens and biofilms can proliferate on the surface of foods or packaging. Microbiological contamination costs the food industry millions of dollars annually in terms of lost or downgraded products [6]. Foodborne pathogens are a major contributor to human illness, hospitalization, and deaths per year. The costs of foodborne illness in the United States is estimated at $152 billion dollars per year for acute medical care and long-term health—related costs, and more than a quarter of these costs, an estimated $39 billion, are attributable to foodborne illnesses associated with fresh, canned and processed products [7]. According to the Centers for Disease Control and Prevention, in the United State alone, some 48 million illnesses and 3000 deaths are caused annually by bacterially contaminated foods. *Salmonella spp.*, *Listeria monocytogenes*, *Campylobacter spp.*, *Staphylococcus aureus* and *Toxoplasma gondii* are among the top pathogens causing foodborne illness and death [8].

Faced with this global public health problem, the incorporation of metal nanoparticles in polymeric materials is an excellent strategy to control bacterial growth. Metallic nanoparticles have been widely studied as antibacterial agents due to their recognized toxicity against bacteria, yeast and some virus. These biological properties depend of the metal, size, structure, and large surface of the nanometric particles. Metal oxide nanoparticles such as ZnO, TiO_2, CeO_2, MgO and CaO have been investigated as inorganic antibacterial agents, although the majority of research are currently centered on copper and silver. Examples of the first are studies on TiO_2 suspensions, which have proved to hold effective antibacterial properties towards *E. coli*, *S. aureus*, *B. subtilis*, *P. aeruginosa* and viruses and, in some cases, this behavior appears to be enhanced by UV light activation [9]. Photoactivation of TiO_2 can generate electron hole pairs that generate $O_2•^-$ and $OH•^-$ radicals. These radicals are very effective in degrading organic contaminations as well as in providing an antimicrobial function. However, the use of TiO_2 nanoparticles under UV light can produce genetic damage in human cells and tissues [10]. As with TiO_2, the antibacterial activity of Zinc oxide has been studied largely against pathogenic and nonpathogenic bacteria. ZnO nanoparticles are believed to be nontoxic, bio-safe, and biocompatible and have been also used as drug carriers, cosmetics, and also in medical devices. Silver nanoparticles are definitely the most popular inorganic nanoparticles as antimicrobial agents [11]. Their use as additives has been widely beneficial for the improvement of various plastic products, textiles and coating-based usages [12], therefore placing silver NPs as holders of a wide range of biomedical applications [13]. Several nanocomposites based on chitosan, poly(ethylene glycol), cellulose, PVP-alginate containing silver have been prepared for biomedical applications as antibacterial wound-dressing [14,15,16,17]. Silver nanocoatings could be effective in preventing hospital infections when deposited on intravenous catheters [18]. However, even if introduced 10 years ago in the US and five years ago in UK, the use of silver-coated urinary catheters has been sporadic in clinical practice, probably due to cost implications [19]. Copper nanoparticles, given their unique chemical, physical and biological properties are of great interest to potential applications in medicine [20–21]. At low concentrations copper is a cofactor for metalloproteins and enzymes, therefore, having the advantage of low toxicity when comparing to other metals. In addition, copper is inexpensive in relation to (3.6 USD/lb) other metals with antibacterial properties such as silver (30 USD/lb), therefore proving to be a cost-effective material [22]. Different polymers have been used as matrices to support copper nanoparticles and generate composite materials with antimicrobial properties. Among these polymeric matrices are: agar [23], bamboo-rayon [24], bovine serum albumin [25], carboxymethylcellulose (CMC) [26–27], cellulose [28–30], chitosan [31–37], cotton [38–40], cotton-cellulose [41], cotton silica [42], epoxy resin [43–44], glass (prepared by Sol-gel) [45], high-density polyethylene (HDPE) [46–47], hydrogel based on acrylamide and acrylic acids [48], linear low-density polyethylene (LLDPE) [49], low-density polyethylene (LDPE) [50], nylon [51], polyamine [52], polyaniline (PANI) [53–54], poly(D,L-lactide-*co*-glycolide) [55], poly(ethylene glycol diacrylate) hydrogel [56], polylactic acid [57], polymers based on acrylic acid, acrylonitrile and methyl methacrylate [58], polymethylmethacrylate (PMMA) [59], polypropylene [60–63], polystyrene (PS) [64], poly (styrene-co-sulfonic acid) [65], polythiophene [66], polyvinyl alcohol (PVA) [67], polyvinyl chloride (PVC) [68], polyvinylmethylketone (PVMK) [69–70], polyvinylidenefluoride (PVDF) [71], and silica [72–73].