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Potential applications of silver nanoparticles

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Abstract

Due to their ability to fight off bacteria, viruses, and fungi, silver nanoparticles (AgNPs) are often utilized in biotechnology. They are created via the use of chemical, physical, and biological processes. AgNPs provide efficient remedies for seven primary problems, including antibacterial, antiviral, anticancer, bone healing, bone cement, dental applications, and wound healing, according to a bibliometric review of 10,278 papers from 2010 to 2020. Due to their intriguing characteristics and promise for personalized healthcare, silver nanoparticles (AgNPs) have attracted a lot of attention in the field of biomedical applications. These nanostructures have the potential to be used as antibacterial agents, drug delivery systems, detection platforms, biomaterials, tissue regeneration agents, and therapeutic alternatives with improved performance. For their development, it is essential to comprehend how their biological interactions and possible harmful consequences work. The inherent anti-inflammatory, antibacterial, antiviral, and antifungal properties of AgNPs are discussed in this paper.

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Introduction

Silver has been recognized since ancient times for its medicinal benefits in wound healing and hygiene in food and water conservation [Silver, 2006; Morones-Ramirez 2013]. The antibacterial properties of silver have been at the center of scientific interest for the past few years, as many studies have shown silver's potent toxicity to many strains of Gram-positive and Gram-negative bacteria [Silver, 2006; Morones-Ramirez, 2013; Hassabo, 2015; Sondi, 2004; Phu, 2010; Feng, 2000; Uttayarat, 2012]. This allows silver to have many biomedical applications, such as infection prevention, wound healing, and disease prevention. A recent study also reported that silver can improve the bactericidal activity of antibiotics against bacteria and biofilms that have become a problem in the medical field [Morones-Ramirez, 2013]. Advances in nanotechnology have led to the development of promising silver nanoscale products for applications ranging from electronics to biomedicine. The main properties of silver nanoparticles (AgNPs) focus on their ability to control their size, shape, and distribution [Cheng, 2014]. Colloidal AgNPs can be prepared by reducing silver ion (Ag+) precursors to zerovalent (Ag0) nuclei, which are stabilized by surfactants or polymers during growth to prevent aggregation of large particles [Hassabo, 2015; Phu, 2010; Cheng, 2014; Grzelczak, 2020; Chen, 2007; Uttayarat, 2015].

Nanotechnology is growing rapidly due to the emergence of nanomaterials, especially inorganic nanoparticles (NPs) and nanorods, which have unique functional and size-dependent physicochemical properties different from their materials [Ju-Nam, 2008]. The potential of inorganic nanoparticles has been explored worldwide for use in nanomedicine, drug delivery and biomedical devices, cosmetics, radiation, radiation, and environmental protection [Lu, 2007; De, 2008; Ghosh Chaudhuri, 2015]. Among inorganic nanoparticles, silver nanoparticles (AgNPs or silver nanoparticles) have attracted researchers in many laboratories due to their novel chemical, physical, and biological properties compared to bulk forms [Sharma, 2009]. AgNPs have physical and chemical properties such as thermal and electrical conductivity, surface-enhanced Raman scattering, chemical stability, catalytic activity, and nonlinear optical behavior [Krutyakov, 2008]. These properties make AgNPs important for use in inks, electronic devices, and medical applications [Monteiro, 2009; Haider, 2015].

Burns and serious illness were the main causes of death in the Middle Ages. Since then, silvers have been introduced and have received centuries of attention in medicine because they can inhibit the growth of diseases. Silver sulfadiazine was first used as an antiseptic in the treatment of burn patients in the 1960s [Klasen, 2000; Silver, 2003; Atiyeh, 2007] and has long been used for the treatment of various conditions such as cauterization, pleurodesis, and skin cuts. company [Tian, 2007; Antonangelo, 2006; CHU, 1988]. Silver nitrate solution, commonly known as "Crede' prophylaxis", prophylactic treatment by dripping silver nitrate solution into the neonatal conjunctiva is now considered standard practice in obstetric research, medical records show increasing pain [WYATT, 1990; Bechert, 2000] and biomaterials [Bechert, 1999; Wr, 1939]. As the amount of antibiotics is smooth, the number of and spend is increasing both in the environment and the body. For example, their role in increasing white blood count has been demonstrated [Jeong, 2014].

Synthesis

Algae are a suitable and worthwhile source for the production of metallic nanoparticles given their abundance and simplicity of access [Ali, 2011]. The synthesis of nanoparticles using algae can be accomplished in three steps: (a) preparation of algal extract in water or an organic solvent by heating or boiling it for a set period, (b) preparation of molar solutions of ionic metallic compounds, and (c) incubation of algal solutions and molar solutions of ionic metallic compounds under controlled conditions, either with continuous stirring or without stirring [Benelli, 2019]. NP production is dose-dependent and also depends on the kind of algae [Ghodake, 2018] employed. Metal reduction is caused by a range of biomolecules, including polysaccharides, peptides, and pigments. Proteins, via amino groups or cysteine residues, and sulfated polysaccharides [Jasni, 2021], stabilize and cap metal nanoparticles in aqueous solutions [Shrivas, 2016]. The synthesis of nanoparticles using algae requires less time than the other biosynthesizing [Jasni, 2021] processes. Several seaweeds, including *Sargassum wightii* and *Fucus vesiculosus*, have been utilized to create silver nanoparticles [Ali, 2011; Ghodake, 2018] of various sizes and forms [Singh, 2023].

Applications

AgNP has been used for over 150 years and has been r ecognized as an antibiotic in the USA since 1954 [Now ack, 2011]. Below are a few thoughts on the use of money by the ancient Egyptians and Romans. The most stable oxidation states of Ag are + 0and +1, but they can also exist in other oxidation states and form various complexes.Ag(NO3) is considered the precurs or for the synthesis of AgNPS. The size and geometry of AgNPs depend on the synthetic materials used for t heir synthesis; However, they can be spherical, rod, and triangular or coated with polymers, biomolecules, and sugar. AgNPs have many chemical, physical, and biological functions that are individually described.

Fig. 1. Application of silver nanoparticles in different fields.

Textiles

The fabrication of functionalized fabrics with silver na noparticles is responsible for the quality of functionali zed fabrication materials [Walser, 2011]. Brazer *et al.* proposed a model in which fabrics and polyethylene bags treated with AgNPs are conside red important in controlling the amount in the air [Blaser, 2008]. Garments such as socks, T-shirts, and sportswear have been studied with AgNPs, but the most beneficial use of AgNPs is thought to be in m edicine since surgical gowns have a high risk of conta mination [Benn, 2008]. Freeman *et al.* reported the effect of AgNPs functionalized fabrics on infectious diseases. Among them, AgNPs functionalized fabrics have an important role in preventing bacterial colony growth [Tran, 2013; Sintubin, 2012; Freeman, 2012; Li, 2008; Liu, 2010]. Many strategies have been used to develop functional materials of AgNPs; For ex ample, the best known most relevant process for the p roduction of silver products is to mix AgNPs with fabr icated materials to embed AgNPs into functional mate rials, or This is followed by immobilization (to functio n) with AgNPs. on fabric. However, besides the advan tages of such materials, they also have disadvantages such as the accumulation of silver ions during cleaning, which is considered to be a major issue for the long-term performance of AgNP functional materials [Freeman, 2012; Li, 2008; Geranio, 2009]. In addition, the composite material containing AgNPs in the sheath has been shown to have good antibacter ial properties in students that affect the fabric contain ing AgNPs [Yeo, 2003].

Food Packaging

As already discussed, the merits of AgNPs functionalized fabrics, as well as Ag-NPs, have also gained traction in the food packaging industry and are known to be one of the important components in packaging materials used for long-term food preservation. For example, materials whose surfaces are coated with Ag-NPs may be useful in preventing contamination of canned foods (preventing contamination caused by microbes) due to the slow release of Ag-NPs from the coated surface along with the prevention of microbial growth on the surface of the packaging material (the effect of Ag-NPs against microbes will be discussed in detail in a later part of this review). Researchers dealing with food preservation yield report sonochemical coating, a simple and versatile technique used to prepare coating materials from a colloidal solution containing

Ag-NPs using ultrasound [Samberg, 2011]. The coating was shown to be effective against different strains of bacteria (gram-negative *E. coli* and gram-positive bacteria S. aureus). The method proved to be a step forward in the synthesis of materials with the help of which food can be preserved for a longer period. Cushen said that Ag-NPs have significance in research related to food preservation and the packaging industry. However, EFSA (European Food Safety Authority) allows only limited forms of Ag-NPs to be used in food packaging and preservation [Cushen, 2012].

Plastic Coatings

The importance of Ag-NP in the preparation of medical devices can be judged from the fact that a wide range of medical devices is prepared from it for their effectiveness against different strains of bacteria (gram-positive and gram-negative). Catheters are usually prepared from materials that contain Ag-NPs to prevent infection and contamination. These catheters are useful for the sustained and targeted release of Ag ions from Ag-NPs, which ultimately inhibit microbial activity. Roe *et al.* synthesized Ag-NP-coated catheters. From the obtained results, the authors concluded that along with the inhibition of biofilm formation, these catheters were non-toxic and showed a sustained release of Ag-NPs [Roe, 2008]. In hospitals, products made of Ag-NPs are used as protective materials against microbial activity; usually, these protective materials are made of plastic containing Ag-NPs on the surface or inside the plastic materials. In addition, Ag-NP-coated materials can be used to prevent microbial activity in water; for example, Doolette *et al.* revealed that Ag-NP coating can be effective in preventing microbial activity in water [Doolette, 2013; Thiwawong, 2013].

Nano prism Preparation

Recently, scientists have turned their attention to the synthesis and optical activity of Ag-NP nanoprisms. Ag-NPs have a unique optical activity that results in surface plasmon resonance (SPR) peaks at relatively long wavelengths. A variety of physical and chemical processes are used to make nanoprisms, mainly silver. One of the processes for making Ag-NPs nanoprisms is the lithography technique (nanosphere lithography (NSL)). In this method, silver nanoparticles are synthesized and kept on a solid substrate whose shape can be controlled to make nanoprisms. Although these lithographic techniques are considered alternatives to solution phase techniques, chemical techniques are more versatile compared to physical techniques.

So far, two main chemical techniques have been identified as prominent among all others: (a) chemical reduction and light-induced aggregation of Ag-NP nanoparticles [Bastys, 2006]. The latter has become very popular recently. Calgary *et al* reported that filtering during illumination directly affects the morphology of nano prisms prepared from silver nanoparticles. In a detailed mechanistic study, Callegari *et al* [Callegari, 2003] suggested that the entire process is controlled by the charge distribution on the silver nanoparticles during light irradiation induced using a laser beam of a specific wavelength. In another reported study, researchers in that group modified light induction techniques using low-intensity light-emitting diodes (LEDs) with different emission wavelengths in combination with different color filters for illumination. We suggested that it is possible to prepare nano prisms of Ag-NPs with a high aspect ratio so that the in-plane dipole plasmon resonance is transferred to wavelengths higher than micrometers. In addition, they also proposed a mechanism to justify the reported studies [Bastys, 2006; Jin, 2003].

Communication loss and signal contamination can be reduced by using silver nanoparticles (Ag-NP), which have a high absorption coefficient of about 1.55 µm, to coat communication fibers. In addition, it can be used in other fields such as biotechnology as a targeted local heating system using low-energy radiation [Loo, 2005]. Shah Jamali *et al.* synthesized gold-coated Ag-NP nanoprism without surfactants. The gold coating provided the stability of the Ag-NPs nano prism against etching, the nano prism had clean surfaces, and the purity gives these gold Ag-NPs nanoprisms applications in the fields of biosensing and bioimaging [Shahjamali, 2012].

Antibacterial Properties

Ag-NPs are known for their strong antibacterial activity against various bacterial strains including highly pathogenic bacterial species (gram-positive and gram-negative bacteria) [Marambio-Jones, 2010]. Sondi and Salopeck-Sondi investigated the antibacterial activities of Ag-NPs against *E. coli* on Luria-Bertani agar plates. Bacterial strains of *E. coli* were used as representative species for Gram-negative bacteria. After analyzing the obtained results, the authors reported that the antibacterial activity of Ag-NPs against *E. coli* was dose (concentration) dependent. Under optimized experimental parameters, they found that Ag-NPs adhered to the cell wall of Gram-negative bacteria (*E. coli*), which destroyed the bacterial cell [Sondi, 2004]. In another published study, researchers performed experiments on the size-related properties of Ag-NPs on different types of Gram-negative bacterial strains [Morones, 2005]. The results obtained from their study indicate that the size of Ag-NPs is an important factor in preventing bacterial cells from performing their normal functions. Furthermore, they also reported that the smaller particles can easily adhere to the cell wall of bacterial cells, thus hindering their normal behavior such as permeability and respiration along with the release of Ag ions from the Ag-NP particle. Furthermore, in another published study, researchers performed experiments to elucidate the dose-dependent properties of Ag-NPs on Gram-negative and Gram-positive bacteria; the authors reported that gram-negative bacteria (*E. coli*) could be inhibited at a relatively low concentration compared to gram-positive bacteria (*S. aureus*). Srivastava *et al.*, revealed that the antibacterial activity of Ag-NPs is both size- and dose-dependent; further, they also proposed a possible mechanism for the antibacterial activity of AgNPs, stating that the antibacterial activity of AgNPs is controlled by the adhesion and penetration pattern of Ag-NPs into the bacterial cell wall, which ultimately leads to abnormal function [Shrivastava, 2007]. In a study published by Pale *et al.*, the authors revealed that the antibacterial activity of Ag-NPs is dependent on the structure (morphology) [Pal, 2007].

Antifungal

Fungi are believed to play a major role in causing fungal infections, especially in hospitals [63]. Along with the antibacterial activities of Ag-NPs, numerous studies on the antifungal activities of AgNPs have been reported, revealing that Ag-NPs could be used as an effective antifungal agent because Ag-NPs exhibit excellent antifungal properties against various fungal species. A report published by Kim *et al.* tested the antifungal activities of Ag-NPs against various fungal strains such as *Trichophyton mentagrophytes* (*T. mentagrophytes*) and *Candida albanicans* (*C. albanicans*) and revealed that Ag-NPs exhibited good antifungal activity. Furthermore, they also proposed a possible mechanism for the antifungal activity of AgNPs, which states that Ag-NPs cause abnormalities in the fungal cell wall, leading to abnormal functions (retardation of normal budding) of fungal cells (*C. albanicans*) [Tran, 2013; Kim, 2008; Monteiro, 2013]. In another published work, researchers found that catheters coated with Ag-NPs can lead to complete inhibition of a fungus (*C. albicans*). Recently, researchers reported the antifungal activities of Ag-NPs synthesized by the tollens method. From the obtained results, they revealed that yeast cell proliferation could be inhibited by Ag-NPs without harming human fibroblast cells. Another published work reported that Ag-NPs showed antifungal activities against various fungal strains such as *C. albicans, C. glabrata,* and *Trichophyton rubrum* (*T. rubrum*), but the activity is dose-dependent [Monteiro, 2013]. In summary, considering the available literature on the antifungal activity of Ag-NPs, it can be concluded that Ag-NPs can be used as an antifungal agent against various strains (species) of fungi and can be useful in overcoming various fungal infections caused by fungi.

Antiviral Agent

Recently, the increase in infectious diseases caused by viruses such as SARS-Cov, influenza A/H5N1, influenza A/H1N1, Dengue virus, HIV, HBV, and new encephalitis viruses, is of prime concern. These infections can create havoc in no time because of their rapid proliferation (glimpses of destruction caused by these viral infections have been observed in some countries and the most dangerous of these viral infections were bird flu, swine flu, and dengue), ultimately resulting in causing severe damage to health and wealth of humans' beings [Coker, 2011]. Ag-NPs are famous for their antimicrobial activities; therefore, researchers have diverted their attention and started evaluating the importance of Ag-NPs in controlling infectious diseases caused by pathogens and viruses. However, the number of reported works using Ag-NPs for controlling viral infections is very low but still, it can pave the way for other researchers to show their interest in dealing with viral infections using nanoparticles specifically Ag-NPs. Elechiguerra *et al.* published their study conducted to assess the effect of Ag-NPs on the HIV-1 virus.

The authors concluded and revealed that the interaction between Ag-NPs and viruses is size-dependent (small-sized nanoparticles are more effective against these viruses) [Elechiguerra, 2005]. hey further enlightened the idea that Ag-NPs get adhered to the Sulphur present in the gp120 glycoprotein knobs that results in hampering the normal activities of the virus and therefore hindering the normal functions of the virus. His mechanism was seconded by another group of researchers when they published their report after assessing the role of Ag-NPs on HIV [Elechiguerra, 2005]. According to their published article, they proposed that Ag-NPs were effective against the HIV having the capability to bind to the Sulphur present at gp120 glycoprotein knobs thus ultimately retarding their normal functions and binding to the hosts [Tran, 2013; Elechiguerra, 2005]. Furthermore, in a published article the authors reported that Ag-NPs play a vital role in inhibiting the synthesis of HBV RNA and extracellular virions in vitro (hepatitis B virus using HepAD38 cell line) [Tran, 2013; Lara, 2010]. Sun *et al.* published their research work in which they conducted experiments on the PVP (polyvinylpyrrolidone) coated Ag-NPs in combination with protein for controlling the infection caused in HEp-2 cells by syncytial virus (RSV) [Sun, 2008]. They revealed that PVP-coated Ag-NPs are effective in preventing RSV virus infection. Furthermore, they proposed a possible mechanism that stated that the PVP-coated Ag-NPs bind to the G proteins present on the surface of the viral cell thus suppressing the adhesion of the RSV virus cells to the host cells. Other researchers experimented on Ag-NPs (having different sizes and geometry) and reported that Ag-NPs are very effective in inhibiting the normal functions of the monkey virus [Rogers, 2008]. De Gusseme *et al.*, reported the usefulness of bio-AgNPs (biogenic Ag-NPs), and they concluded that both AgNPs and ionic Ag+ play very important roles in controlling murine norovirus [De Gusseme, 2010]. Xiang *et al.* conducted experiments to elucidate the inhibiting role of Ag-NPs against the H1N1 influenza A virus. In the report, the authors revealed that AgNPs are very effective in inhibiting the normal activity of the H1N1 influenza A virus [Xiang, 2013]. Furthermore, they proposed that Ag-NPs can control the apoptosis of MDCK cells caused by the H1N1 influenza A virus. In short, almost all of the reported articles suggested the same mechanism which states that AgNPs get adhered to the outer proteins of the viral cells thus ultimately inhibiting the normal function of the viral cells. However authentic mechanism is yet to be established but Ag-NPs are considered to play a pivotal role in the future for controlling infectious diseases caused by viruses [Galdiero, 2011].

Wound Dressing

Wound dressings (dressings) functionalized with silver nanoparticles (Ag-NPs) are commercially available and often used for medical purposes to treat various infections such as burns, toxic epidermal necrolysis, Steven-Johnson syndrome, chronic ulcers, and pemphigus [Tran, 2013]. In typical dressings (wound dressings), Ag-NPs are coated on the surface of a polyethylene layer. Experiments showed better wound healing properties of Ag-NP coated dressings (wound dressing) compared to wound dressing without Ag-NPs. Such a wound dressing can prevent infections along with minimizing healing time without any side effects [Ahamed, 2010]. In a paper published on Ag-NPs, researchers concluded that bandages (wound dressings) containing Ag-NPs minimize the healing time of burns. However, no difference was found in the healing time of deep burns [Ahamed, 2010]. In a report published by the research group, the authors suggested that a dressing composed of Chitosan/silver nanoparticles (Cs/Ag-NP) showed a higher healing rate compared to a conventional wound dressing; further, they used Chitosan as a control in their experiments. The use of Ag-NPs in wound dressings may be useful in eradicating skin-related problems [Xing, 2010]. In one of the published reports, researchers incorporated Ag-NPs into chitin scaffolds, which were later used as a wound dressing. From their experiments, they concluded that the wound healing and antimicrobial efficacy of chitin are further enhanced by the incorporation of Ag-NPs [Tran, 2013; Madhumathi, 2010]. Furthermore, in another published paper, researchers revealed after an extensive study that a hydrogel made of β-chitin and Ag-NPs can be effective in preventing various infections that may occur in wounds [Kumar, 2010]. In another published paper, researchers reported that by incorporating Ag-NPs (less than 20 nm in size) into guar gum [Jeon, 2008], a new cationic biopolymer demonstrated faster healing and improved cosmetic appearance. In addition, the biopolymer matrix acted as a hydrated surface that aided cell proliferation. The antimicrobial activity of Ag-NP functionalized wound dressings is largely dependent on the concentration, and release of silver along with its distribution and degree of wet ability [Chopra, 2007]. The importance of Ag-NPs in dressings (wound dressings) has been recognized by the scientific community and may be helpful in the preparation of new materials containing Ag-NPs that may eventually be used in future medicine [Sharma, 2009].

Anticancer

Caspase-mediated synthesis, as well as other morphological alterations such as membrane integrity impairment, cell growth decreased, cytoplasmic condensation, and so on. AgNPs with IC50 values of 63.37, 27.54, and 23.84 μg/mL against normal African monkey kidney (Vero), HeLa (cervical), and MCF-7 (breast) cells, respectively, were synthesized by *G. mangiferae* extracts, which are biocompatible and encompass promising candidates for a range of biopharmaceutical as well as agricultural applications [Chung, 2016; Mathur, 2017; Maurya, 2023].

Environment

Air disinfection

Bioaerosols are airborne particles of biological origin, including viruses, bacteria, and fungi, which are capable of causing infectious, allergic, or toxicogenic diseases. In particular, bioaerosols from indoor air have been found to accumulate in large quantities on heating, ventilation, and air conditioning (HVAC) system filters [Yoon, 2008]. It is found that outdoor air pollution and poor sanitation of HVAC equipment often organic or inorganic materials deposited on the filter media after air filtration contribute to microbial growth. The WHO has estimated that 50% of biological contamination present in indoor air comes from air handling systems, and air filters have been found to harbor harmless microorganisms such as bacterial and fungal pathogens. Most of these pathogens produce mycotoxins that are dangerous to human health, so microbial growth in air filters is limited by integrating antimicrobial Ag-NPs into air filters. The antimicrobial effect of Ag-NPs on bacterial contamination of activated carbon filters (ACFs) was studied by Yoon *et al.* [Yoon, 2008].

The results showed that Ag-coated "ACF filters" effectively remove bioaerosols. Analysis of the antibacterial activity of Ag-coated "ACF filters" showed that two bacteria "*Bacillus subtilis*" and *E. coli* were completely inhibited within 10 and 60 minutes, respectively. It was found that silver deposition did not affect the physical properties of ACF filters, such as pressure drop and filtration efficiency; however, adsorption efficiency was reduced by silver deposition. Therefore, the authors additionally suggested that the number of Ag-NPs on "ACF filters" needs to be optimized to avoid excessive reduction of their adsorption properties and to show effective antimicrobial activity. Recently, Jung *et al.* [Jung, 2011] generated Ag-coated CNT hybrid nanoparticles (Ag/CNTs) using aerosol nebulization and thermal evaporation/condensation processes and considered their applicability for antimicrobial air filtration. Aerosols of CNTs and Ag-NPs mixed and attached to form Ag/CNTs. The antimicrobial activity of Ag/CNT coated filters was tested against Gram-positive bacteria *S. epidermidis* and Gram-negative

E. coli. It was found that when Ag/CNTs were deposited on the surface of the air filter media, the antimicrobial activity against the tested bacterial bioaerosols was enhanced compared to the deposition of CNTs or Ag-NPs alone, while the filter pressure drop and bioaerosol filtration efficiency were hardly similar to those of the deposition CNT. It was reported that the surface area of Ag-NPs was increased by CNTs, so it is the main reason for the higher antimicrobial filtration efficiency of Ag/CNTs compared to pure Ag-NPs. Polymeric air filters made of polypropylene and silver nitrate ($AgNO_3$) were investigated for bacterial survival [Miaśkiewicz-Peska, 2011]. The study shows that adding the antibacterial agent $AgNO_3$ to the filters was effective in preventing bacteria from colonizing the filters. The presence of the antimicrobial compound $AgNO_3$ in air filters reduces the number of bacteria, which was observed in both gram-negative and gram-positive bacterial strains *Micrococcus luteus, Micrococcus roseus, B. subtilis,* and *Pseudomonas luteola*. The apparent reduction in bacterial cell growth on silver-treated filters has made antimicrobial filter treatment technology a real necessity for the future.

Water disinfection

Water is one of the most important substances on Earth and is essential for all living things. About 70% of the Earth is covered in water, but only 0.6% is suitable for human consumption. Safe drinking water is an important health and social issue in many developing countries [De Gusseme, 2010]. According to the WHO, at least 1 billion people do not have access to safe drinking water. Contamination of drinking water and subsequent outbreaks of waterborne diseases are major causes of death in many developing countries [Pradeep, 2009]. In addition, the spectrum and incidence of some infectious diseases are increasing worldwide, and therefore there is an enormous need for treatment to control microbial contamination of water and reduce the number of water-borne diseases. Considerable interest has emerged in the use of Ag-NPs for water disinfection. Chemically fabricated nano silver (chem-Ag-NPs) can be uniformly decorated onto porous ceramic materials to form an Ag-NPs-porous ceramic composite using 3-aminopropyltriethoxysilane (APTES) as a linker molecule [Lv, 2009]. This composite can be stored for a long time and is resistant to washing without loss of NP. The sterilization properties of the Ag-NPs-porous ceramic composite as an antibacterial water filter were tested with *E. coli*. It was found that at a flow rate of 0.01 L min−1, the outlet E. coli count was zero, while the inlet water had a bacterial load of 105 CFU ml−1. It also confirms that the connection between chem-Ag-NPs and ceramics is based on the coordination bonds between the $-NH_2$ group on top of the APTES molecule and the silver atoms on the NP surface. This kind of connection ensured that the chem-Ag-NPs were firmly attached to the inner walls of the porous ceramic channels so that they could release sufficient silver ions for antibiosis. Such Ag-NP-porous ceramic composites have been successfully tested in drinking water purification [Verma, 2019]. Additionally, chem-Ag-NPs can be coated onto common polyurethane (PU) foams by overnight exposure to chem-Ag-NP colloids [Jain, 2005]. The NPs are stable on the foam and do not wash off with water, and the morphology of the foam is preserved even after coating.

The binding of NP is due to its interaction with the nitrogen atom of PU. At a flow rate of 0.5 L min-1, after a few seconds the outlet E. coli count was zero, while the inlet water had a bacterial load of 105 CFUml-1. “chem-Ag-NPs” were also successfully formed on macroporous “methacrylic acid copolymer” beads for water disinfection [Gangadharan, 2010]. This indicated that the chem-Ag-NPs formed on these copolymer beads by the chemical reduction method were stable when washed under water, and their stability was due to the interaction of “chem-Ag-NP” with the “-COO-” carboxyl functional group to "copolymer beads". Polymeric microspheres containing chem-Ag-NPs showed highly effective disinfection against two strains of Gram-negative bacteria (*E. coli, P. aeruginosa*) and two Gram-positive bacteria (*B. subtilis, S. aureus*). The copolymer beads bound to chem-Ag-NPs were effective in reducing bacterial counts to zero for all strains tested. Bacterial adsorption or adhesion analysis revealed that the "copolymer beads" containing "chem-Ag-NPs" had no bacterial cell adsorption/adhesion.

Bone healing

Bone is an active tissue with the ability to repair itself. However, this ability is usually compromised when bone defects become infected. Large defects created by tumor resection, genetic malformation, or severe trauma can be replaced or restored by implantation of bone grafts. Implant failure is mainly associated with infection and often causes financial burdens, patient suffering, and even death [Cochis, 2016; Gao, 2014]. In addition, it has also been reported that implant-related infections can lead to amputation in patients [Angelini, 2014]. Approximately 50-60% of infections are commonly caused by *Staphylococcus* spp. [Tande, 2014]. These bacteria are commonly treated with antibiotics, but over time these organisms have developed resistance to the antibiotics used. Moreover, they can rapidly form a biofilm in which they are protected against antibiotics, including natural antibiotics [Donlan, 2002]. In this application, AgNPs are used due to their antimicrobial effect in tumor prostheses; and trauma implants in combination with hydroxyapatite coatings and bone cement [98]. Orthopedic infections are typically responsible for bone destruction and implant loosening [Soucacos, 2008]. AgNPs incorporated into crystallized hydroxyapatite (HA) or titanium scaffolds demonstrated significant antibacterial activity against both bacteria [Marsich, 2013]. Felix and Muthu [Felix, 2016] found that AgNP-impregnated bio-scaffolds improved bone healing [Naganthran, 2022].

Bone Cement

Bone cement is used in orthopedic surgery to secure devices in dental and arthroplasty sites, as well as to join broken bones together. The operation consisted of replacing a damaged part of the body with an artificial one as a result of an acute injury or degenerative disease. The most frequently performed operations were disc replacements in the knee, hip, and spine [Prokopovich, 2015]. According to data from the National Healthcare Safety Network, infections occurred in up to 2.3% of joint replacement surgeries in the United States, and the highest rate of infection occurred in 15% of ankle replacement surgeries. Antibiotics have traditionally been administered orally or released from bone cement to prevent infections [Tyllianakis, 2010]. However, the use of antibiotics has led to the development of antibiotic-resistant bacteria. Consequently, a new approach was required and thus a non-antibiotic technique was developed [Prokopovich, 2015]. Perhaps AgNPs were incorporated into bone cement for antibacterial purposes without worsening the cytotoxicity of the material [Buckley, 2010; Ewald, 2011; Naganthran, 2022]

Dental treatment

Plaque formation is a factor contributing to the development of dental diseases. The oral cavity is home to various microorganisms. Polymicrobial communities grow and form biofilms in the oral cavity. These biofilms are capable of causing a variety of local diseases, including peri-implant and periodontal diseases, which can lead to implant failure or tooth loss [Allaker, 2010]. Peri-implants are associated with serious complications after implant replacement [Sivolella, 2012]. Peri-implantitis mucositis occurred in up to 50% of cases and peri-implantitis occurred in up to 43% [Zitzmann, 2008]. Lang *et al.* [Lang, 2011] reported that there was no difference in the formation of bacterial biofilms on tooth and implant surfaces, but that surface roughness could have an effect. Polymicrobial communities include *Streptococcus sanguis, Streptococcus oralis*, *Streptococcus mitis, Eikenella corrodens* and *Veillonella atypickica*. Some dental biomaterials have been incorporated into AgNPs to reduce biofilm formation. Thomas *et al.* [Thomas, 2018] biosynthesized AgNPs using *Bacillus amylolique faciens* SJ14 culture and *Curcuma aromatica* rhizome extract and incorporated into polymethyl methacrylate (PMMA), showed inhibition against cariogenic bacteria, *S. mutans* from colonization of dental restorative material. Biosynthesized PMMA-incorporated AgNPs can be used as a dental material. Modification of the PMMA surface by incorporating an antibacterial agent is supposed to prevent or minimize microbial attachment and posterior colonization [Campos, 2017]. AgNPs were biosynthesized using *Geranium maculatum* leaves. AgNPs are more effective against pathogens such as *Candida albicans* [Acosta-Torres, 2012].

In preventive dentistry, AgNPs have been used to infiltrate carious lesions and precipitate, leading to enamel hardening. Al-Nerabieah *et al.* [Al-Nerabieah, 2020] reported in vivo studies using nano-silver fluoride with green tea extract (NSF-GTE) to stop cavitation lesions and used teeth in preschool children as a subject. The study reported 67.4% effectiveness in stopping carious dentinal lesions in both posterior and anterior primary teeth over six months. Mineral trioxide aggregate (MTA) is one of the materials of choice for the repair of root perforations and was introduced by Torabinejad *et al.* [Torabinejad, 1993]. Many studies report that MTA has been mixed with various additives. In a study conducted by Bahador *et al.* [Bahador, 2013], the in vitro result of the application of AgNPs as a potential mixture of mineral trioxide aggregate (MTA) to prevent *Porphyromonas gingivalis* infection. The results showed that IMTA containing 12% and 25% completely inhibited the proliferation of *P. gingivalis* in a dose-dependent manner in root perforations.

Another study reported the use of AgNPs biosynthesized with aqueous extract of *Mangifera indica* leaves in dental prosthesis applications [Sundeep, 2017]. AgNPs reinforced glass ionomer cement (GIC) increased the mechanical strength of conventional dental implant materials and acts as a surface coating against *S. aureus* and *E. coli*. Paul *et al.* [Paul, 2020] investigated the use of AgNPs synthesized from white pepper oleoresin in testing against oral pathogens such as *S. aureus, S. mutans* and *Pseudomonas* sp. The results indicated that the biosynthesized AgNPs inhibited all three oral pathogens. Similarly, Umai *et al.* [Umai, 2021] reported the testing of AgNPs biosynthesized by *Olea europaea* and tested against major oral pathogens such as *C. albicans* and *S. mutans*. AgNPs inhibited the growth and biofilm formation of *S. mutans* and *C. albicans*. Biosynthesized AgNPs may be beneficial as a surface coating of conventional dental implants to prevent infections. In another, Halkai *et al.* [Halkai, 2018] suggested that AgNPs synthesized by the fungus Fusarium semi tectum showed effective antibacterial activity against endo-perio pathogens such as *P. gingivalis, B. pumilus* and *E. faecalis*. Biosynthesized AgNPs have the potential to be a solution in the treatment of endodontic, periodontal, and combined lesions [Naganthran, 2022].

Conclusion

Silver nanoparticles (AgNPs) are being investigated for biomedical applications due to their favorable physicochemical properties, antibacterial efficacy, and non-toxic nature. Their antibacterial properties are influenced by factors such as size, shape, concentration, surface charge, and colloidal state. The surface area of AgNPs allows coordination of the ligand, which enables surface functionalization.

Numerous studies support their positive effect on innovative biocompatible materials and devices. AgNPs can be synthesized using a variety of methods, with biosynthesis being the most popular method to produce AgNPs for use in the biomedical field. Biomedicine is a branch of medical science that deals with improving the diagnosis and treatment of existing and emerging human diseases. A biomedical pathogen is an organism that can cause disease in the host (human) and transmit the disease to the host (human). The most common AgNP methods are UV-Vis, FTIR, DLS, XRD, and SEM analysis. Since AgNPs are effective and effective against biomedical diseases, their applications in the biomedical field are increasing every year.

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