Review Article

Silver nanoparticles and their applications- A comprehensive review

Mohammad Shahzad Tufail¹ and Iram Liaquat^{1*}

1. Microbiology Lab, Department of Zoology, GC University Lahore, Pakistan

*Corresponding author's email: iramliag@hotmail.com

Citation

Mohammad Shahzad Tufail and Iram Liaquat. Silver nanoparticles and their applications-A comprehensive review. Pure and Applied Biology. Vol. 11, Issue 1, pp315-330. <http://dx.doi.org/10.19045/bspab.2022.110033>

Received: 17/04/2021

Revised: 19/06/2021

Accepted: 22/06/2021

Online First: 12/07/2021

Abstract

The nanotechnology is a rapidly flourishing field with broad spectrum applications in almost every field. It has established that smaller size nanoparticles are more toxic compared to larger ones. Use of silver nanoparticles (AgNPs) has been recognized since the last couple of years. Though many commercial methods are available for their synthesis but biogenic synthesis has proven more efficient and environmentally friendly. AgNPs have shown quite interesting, useable and promising characteristics in various fields of human life. The biomedical applications of AgNPs have gained a huge interest of scientific community, and have significantly improved personalized healthcare practice (various types of surgeries, antibiotics, drug delivery formulations). It has been said that AgNPs have novel antimicrobial applications as anti-bacterial, anti-biofilm, anti-fungal and anti-viral agents. Strong antibacterial activity of AgNPs makes these ideal in fighting against multi drug resistant bacteria (MDR). Similarly, AgNPs also have proven their potential in agriculture field, environment and industrial sector. This review aims to provide an insight on biogenic synthesis and characterization of AgNPs alongwith applications in everyday life from economical, commercial and industrial perspective. Due to easy synthesis and wider availability of AgNPs, they are being considered as important constituent in the preparation of different commercially and bio-medically useful products alongwith enormous use in food packaging system for longer shelf life and prevention of spillage.

Keywords: AgNPs; applications; biomedical applications; mechanism of action; nanoparticles; silver nanoparticles

Introduction

Nanotechnology is the emerging field of science with lots of benefits to humans, animals and nature. Out of many excellent findings of nanotechnology, the nanoparticles (NPs) are very much beneficial. With the advancement in nanotechnology, humans have gained the ability to synthesize nanoparticles in the labs [1]. The particles having nanometers size are known as NPs. There are many kinds of metallic and non-metallic NPs synthesized using metals such as Au, Ag, Ce, Pt, Pd and Zn [2], but most important are silver nanoparticles (AgNPs). The

AgNPs have extensively been studied for their activities particularly antimicrobial activities [3, 4], and emerging as promising nano antibiotics now a day [5]. Because of their broad-spectrum activities, AgNPs grab great attention in the field of biomedical, medicine, agriculture, insect control and several other industries [6]. By using an ecofriendly approach, AgNPs applications have been increased in preparation of large number of products such as pests, electronic devices and in controlling microbe's growth and infection [7, 8].

Synthesis of AgNPs

There are many techniques which can be used for the synthesis of AgNPs. 1). Physical synthesis: In physical method, synthesis of AgNPs taken place by the use of thermal energies. This involves the evaporation condensation reaction in which environmental temperature increased to increase the nuclease reaction. Thus, the production of AgNPs occurs. 2). Photochemical synthesis: It is divided into photophysical and photochemical methods. 3). Biogenic synthesis: living structures are used for the synthesis of AgNPs [9, 10].

Biogenic synthesis

The biogenic synthesis is also known as green synthesis. It is quick, easy, cost effective and environmentally friendly approach compared to physical and photochemical methods as they are

harmful, inflammable and also produce environmental disturbance. It also needs less time and energy resources as compared to physical and photon methods. The other benefits are the availability of biological resources in large amount, high density, natural stability and easy solubility in water [11]. In green synthesis, microorganisms (yeast, bacteria and fungi *etc.*), and different plant tissues (fruit, peel, latex, leaves, stems and root *etc.*) can be used for the synthesis of AgNPs (Fig. 1). Different natural compounds present in plants and also produced by bacteria (proteins, polyphenols, enzymes, amino acids *etc.*) act as reducing and capping agents. The use of microorganisms and agro waste not only reduce price but it is environmentally friendly also [12, 13].

Figure 1. Biogenic synthesis of AgNPs. Microbes and Plant tissues can produce AgNPs from silver salts. Various enzymes and organic molecules enhance nucleation and also play role in AgNPs capping

Properties and Stabilization of AgNPs

The AgNPs have unique properties as compared to their bulk counterparts [14]. Many studies have reported that AgNPs composition and size dependent characteristics have unique physical, chemical, optical, dielectric, electrical, thermal, mechanical, catalytic and biological properties. Their size ranges from 2-100 nm depending upon single surface plasma resonance (SPR) peak between 400-440 nm. But they may have more than one SPR peaks depending upon their morphology [15]. The SPR peaks also depend on the size and metal composition of the NPs [16]. However, in biogenic synthesis of AgNPs, the major focus is their stability. The stability can be achieved by either electrostatic/charge stabilization or polymeric stabilization [17].

In electrostatic stabilization, a charged layer of ionic groups is formed at the surface of nanoparticles, thus creating repulsive force among each other. The charged ions prevent aggregation in between the particles [17]. In case of polymeric stabilization, two types of mechanisms are involved. First, macromolecules are attached to the surface of nanoparticles and steric stabilization is achieved. Following this, depletion stabilization is obtained by macromolecules which are free in dispersion medium. Usually, steric and depletion stabilization is used together with large amount of free polymer interacting with colloidal nanoparticles in the medium [18]. Chemical synthesis of AgNPs may cause the aggregation of particles. This problem is prevented by adding different stabilizer into medium like ammonia, cellulase *etc.* [19]. For bacterial synthesis of nanoparticles, stabilizing compounds (*e.g.* protein) is added to the medium naturally by the bacterial cell. These compounds prevent particles aggregation and provide long term stability [16].

There are many techniques which can be used for the determination of physicochemical properties of AgNPs.

Major of these techniques are UV-visible spectroscopy, X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and fourier transform infrared spectroscopy (FTIR) [20].

Applications

AgNPs have applications in almost every field of life. The major applications of AgNPs were summarized below (Fig. 2).

Antimicrobial applications

Antibacterial potential

AgNPs have excellent antibacterial activity. They are extensively investigated for their antimicrobial activity against broad range of microorganisms including both Gram -positive, Gram - negative bacteria and other microbes like fungus, yeast *etc.* [21]. AgNPs have been reported with excellent antibacterial activity against multi drug resistant (MDRs) like *Pseudomonas aeruginosa*, *Escherichia coli*, *Streptococcus pyogenes*, *Staphylococcus aureus* and *Klebsiella pneumonia* [22]. There are various methods adopted by researchers to check antibacterial sensitivity of AgNPs. The most common are; i) Zone of inhibition (ZI) by disk diffusion and agar well diffusion method, ii) minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC), iii) growth pattern and iv) time kill curve [23].

Mechanism

The AgNPs enter inside the bacterial cell wall and release silver ions or may remain deposited in the cell [24]. They have very small size and can easily pass through the peptidoglycans layer of cell wall and cell membrane [25]. They damage the cellular membrane, disturb the cellular metabolism, generate atomic oxygen (oxidative stress) due to reactive oxygen species (ROS) formation and inhibit the transcription (Fig. 3). The silver ions released by these nanoparticles interact with sulfur and phosphorus molecules present in the proteins associated with cell wall and membrane [26]. Furthermore, the

interaction of cationic silver ions with negatively charged bacterial cell membrane, cause multiple pores in the membrane and thus allows the outflow of intracellular content. This process causes an ion imbalance into the cell and taking benefit, silver ions pass into the cytoplasm through the plasma membrane. Silver ions thus interact with intracellular components which results in bacterial cell death [27]. Many studies have reported silver ions as the inhibitors of the proteins and enzymes activities involved in ATP production. They also inhibit respiratory enzymes which lead to ROS production, damage the DNA and RNA, destabilize and disrupt the outer membrane [28, 25].

The AgNPs are reported to be more effective against Gram negative bacteria compared to Gram positive bacteria. Thick and tough layer of Gram-positive bacteria create hindrance in the entry of nanoparticles into the cell [29]. Since antibacterial activity of AgNPs depends on their shape and size, higher surface area of AgNPs enable these to release large amount of silver ions, which ultimately led to higher activity [30].

The other steps in antibacterial effects of AgNPs are inhibition of cell wall synthesis, nucleic acid synthesis and protein synthesis by interacting with 30S ribosomal subunit [31]. The strong antibacterial effect of AgNPs against the MDRs is because of their ability to damage the bacterial cell in multiple ways, for example by disrupting intracellular pathways [32], damaging DNA and proteins [33], and generating reactive oxygen within the cell [34].

Significance of AgNPs antibacterial properties

The commercially available antibiotics are becoming less effective against bacterial pathogens [35] due to increased microbial resistance. In particular, MDR bacterial pathogens are becoming serious threat to human population by using their efflux pump efficiently and biofilm formation. Their everyday increasing number of MDRs is leading to severe public health

risk [36, 37]. MDRs not only have deleterious effects on human health but also cause serious threat to several fields of human activity like agriculture, aquaculture, veterinary as well as wildlife [36].

The AgNPs is the need of hour to combat the MDR bacterial pathogens [37, 38]. The NPs have advantages as there is generalized mode of action against bacterial pathogens. Compared to commercial antibiotics, they effectively control MDR using various methods such as by 1) disrupting cell wall and plasma membrane [39], penetrating and intracellular damaging *i.e.* disrupting intracellular pathways [32], damaging DNA and proteins [33], generating reactive oxygen within the cell [40, 41]. Therefore, AgNPs can be important in handling antibiotic resistance of pathogenic bacteria. Moreover, the production of AgNPs is a cheap process and can be produced by eco-friendly methods with minimal environmental disturbance [42].

Antibiofilm potential

The biofilms of pathogenic bacteria are responsible for major infections and increased resistance against standard antibiotics. In this scenario, AgNPs are the potential solution to this stress [43]. The AgNPs was reported to inhibit the biofilm formation of *P. aeruginosa* and *E. coli* at very low concentration (0.2 µg/mL). The AgNPs inhibited the biofilm formation of *K. pneumonia* and *S. aureus* at the concentration of 0.0596 µg/mL and 0.0683 µg/mL, respectively [44, 45]. Because of their extremely small size and higher volume ratio, the AgNPs can penetrate into the mature biofilm. Hence, efficiently inhibit the biofilm formation of different bacteria.

Antifungal potential

Fungal infections are also threatening life on earth [46, 47]. The cases of death by fungal infections are increasing day by day. Among fungal pathogens, the *Candida* sp. is more common and responsible for 40% death [48]. The AgNPs are also reported to be effective against many opportunistic

human fungal pathogens. Because of these antifungal properties of AgNPs, they are being considered as potent and fast acting fungicides against fungal pathogens [46]. Recently AgNPs were found to have antifungal properties against *Aspergillus niger*, *Candida glabrata*, *C. albicans*, *C. krusei*, *C. parapsilosis* and *Trichophyton interdigitale* [49, 47].

Antiviral potential

Similar to antibacterial and antifungal properties, AgNPs also passes antiviral properties. Available literature suggests that AgNPs are effective against viral particles. They bind with viral particles on surface and inhibit the virus-host interaction [51]. For example, the AgNPs of size 1-10 nm become attached to the human immunodeficiency virus (HIV) via preferential binding to the exposed sulfur containing residues of the gp120 glycoprotein knobs. Hence, HIV virus losses its ability to bind with host cells [52]. Similarly, AgNPs were also found to be active against hepatitis B virus (HBV) and effectively inhibit the production of HBV RNA [51].

Environmental applications

AgNPs possess many environmental applications. Few of them have been described below.

Air disinfection

We are inhaling plenty of harmful microbes present in air. Bio aerosols are airborne particles like viruses, bacteria, fungi *etc.* World health organization (WHO) has reported that 50% of biological contaminations in indoors come from air handling systems. Many harmful microbes are also reported in air filters which are responsible for the production of mycotoxins. Mycotoxins are very dangerous to human health. AgNPs based air filters have greatly reduced this problem of air contamination. The activated carbon filters (ACF) with the association of AgNPs were also reported to be very effective for the removal of bioaerosols [53].

Water disinfection

As AgNPs are widely known for their activity against large number of microbial pathogens particularly against MDRs. Due to these antimicrobial properties and durability of AgNPs, they are also being considered to control water borne diseases. Recently, many studies have explored water disinfectant ability of AgNPs [54-56]. A study suggested that AgNPs can be effectively used as disinfectant in water purification system [57]. Furthermore, AgNPs can also be used for hand washing and personal hygiene. In another study, the authors reported that AGNPs coated filters showed 100% bacterial inhibition [58].

Surface disinfection

AgNPs based paints are getting more interest for researchers. Such paint have been found to be environmentally friendly and showed antimicrobial properties against many pathogens [59, 60]. Furthermore, AgNPs coating led to improved food preservation and inhibited the microbial growth for longer times [60]. AgNPs were used in making suits worn by medical healthcare personals. Such suites were found to possess antibacterial activity, thus offered protection to healthcare workers [61].

Biomedical applications

Cancer therapies

The AgNPs are reported as an excellent tool against cancer. Authors have reported that AgNPs value of LC₅₀ (63.37, 27.54 and 23.84 µg/mL) was effective against African monkey kidney, HeLa cell line and MCF-7 (breast) cells, respectively. On the basis of their results, they suggested that AgNPs can be further characterized and used as active anticancer agents in future anticancer therapies [62].

Antidiabetic

The antidiabetic activity of AgNPs activity was monitored by synthesizing AgNPs from *Tephrosia tinctoria* stem's extract. It was observed that AgNPs scavenged free radicals, resulted in decreased level of enzymes (α -glucosidase and α -amylase) that are responsible for the hydrolysis of

complex carbohydrates. Consequently, this resulted in an increased consumption rate of glucose [63].

Wound healing

Wound infections are a major challenge in medical field. These are responsible for large number of morbidity and mortality worldwide and lead to accountable economic loss [64]. AgNPs based dressings have been successfully applied to wounds. The AgNPs present in the dressing interact with bacteria present in the wound and destroy them [65].

Additionally, AgNPs play important role in the recovery of damaged skin [66]. It was reported that naturally available biopolymers in combination with AgNPs, significantly improved wound healing process [67]. Previously, food and drug administration (FDA) department of United States (US) approved many bio composites modified with AgNPs due to their remarkable role in wound healing process [68, 69].

Bone healing

Bone diseases like cancer, fractures, genetic conditions *etc.* are threatening life of millions of peoples worldwide [70]. Opportunistic pathogens cause infections in bone implants and led to high morbidity, annually [71]. In this scenario, AgNPs play very important role. Because of their broad-spectrum role against pathogens, they kill microbes causing infection in bone implants. In contrast of their antimicrobial activity, they also inhibit biofilm formation in ortho implants [72]. The bone cement with AgNPs is highly antibacterial in nature [73]. Furthermore, the AgNPs are being used in doping material for synthetic and bio-inspired bone scaffolds during the last few years [74].

Catheters

The AgNPs also have active use in catheters. Scientists have successfully developed a method in which a very thin (100 nm) layer of AgNPs can be coated on the surface of catheters. The catheters coated with AgNPs are biocompatible and are nontoxic. They have the tendency to

release silver ions on implantation sites [75]. The risk of infection has decreased dramatically due to the coated layer of AgNPs on the surface of catheters. These catheters have the ability to inhibit the growth and biofilm formation of drug resistant pathogenic bacteria [76].

Teeth material

AgNPs are also being successfully used in the material used to fill teeth. The incorporation of AgNPs in composite resin has increased the antimicrobial and mechanical properties of resin [77]. Authors have reported that material used for filling of teeth cavities with the addition of AgNPs enhanced the anti-bacterial activity against many MDR bacteria like *Streptococcus milleri*, *S. aureus* and *Enterococcus faecalis* [78].

Agricultural Applications

AgNPs also have many applications in the field of agriculture (Fig. 4).

Pest management

Insects (known as pests) are responsible for a huge loss to agricultural products. They destroy leaves, flowers, fruit, stored food and lead to worldwide economy loss. They also have adverse environmental and human health effects [79]. The excellent antilarvicidal and insecticidal effects of AgNPs have promising effects against these insects [80].

Likewise, published data reported that AgNPs have effectively controlled the *Sitophilus oryzae* pest which affects rice and wheat grains [81].

Plant Growth Enhancement

AgNPs have been successfully used for the enhancement of seed germination and plant growth [82]. In a case study, multiwalled nanotubes with nanoparticles were used for the growth enhancement of tobacco cell culture in the range of 5-500 µg/mL concentration. The result showed that nanoparticles enhanced the cellular growth of tobacco plant. AgNPs also improved soil fertility and promoted stress tolerance in plants. AgNPs based Nano sensors also proved beneficial in precise farming [83].

Miscellaneous industrial applications

Textile industry

AgNPs have various uses in textile industry. Their common use is in the processing of T shirt, sporting clothes, undergarments, socks *etc.* [84]. Because of their antibacterial activity, AgNPs have been used in cloth making. AgNPs fabricated on cotton cloth showed antibacterial activity against *Corynebacterium*, a sweat bacterium [85]. In another study, [86] reported that the incorporation of AgNPs in cotton cloth showed antibacterial activity against *E. coli*.

Food industry

Microbial spoilage of food is a big threat to food industry. Also food borne diseases alongwith shortage of food are increasing. This forces scientists to develop new methods to preserve food. Among many methods to preserve food, NPs based food storage method is proving more efficient [87, 88]. AgNPs based food packaging of fresh fruits, vegetables and meat has resulted in increased shelf life [87].

Previously, authors evaluated the effect of AgNPs polyvinylpyrrolidone (PVP) coating on preservation of fresh vegetables [89]. They reported that AgNPs coating showed interesting results, as there was no change in coloration, decreased weight

loss, no microbial growth and fresh vegetable even after 10 days. In another study, authors also investigated the effect of AgNPs coated films on the fresh fruits and vegetables [90]. They observed that AgNPs coating inhibited the growth of microbes. Similarly, the effect of AgNPs on packaging of meat was studied. Authors stored the meat coated with AgNPs polyvinylchloride PVC at 4°C temperature in refrigerator and observed that no microbial growth on meat even after 7 days. This proved increased shelf life of meat which otherwise usually got spoiled in just 2 days [91].

Chemical industry

The Li ion batteries are the well-known source of energy. This depends on their cathode and anode materials [23]. Nanomaterial-based material could improve the Li ions batteries (LIBs) in terms of their capacity and cycle stability [92]. The NPs based nanocomposites were found to be better for electrochemical storage [93, 94]. Therefore, nanocomposites based on NPs as potential material may be used in electrodes of LIBs due to their physico chemical properties and their electrical conductivity [95, 96]. In addition, AgNPs have the ability to enhance the rate of electron transfer and analytical sensitivity [97, 98].

Figure 2. Applications of AgNPs in various fields were summarized

Figure 3. Antimicrobial action of Silver nanoparticles (AGNPs). A. Nano silver alpha attaches to cell membrane creating pores to cause cellular leakage, B. distort cellular morphology; C. breaks dsDNA; D. inhibits DNA replication; E. interacts with 30S ribosome; F. inactivate vital enzyme; G. denature protein; H. modulate cellular signaling; I. generate ROS, which act on DNA and cell membrane; J. release silver ions, which affect the normal functioning of membrane protein; and K. accumulate inside the cell in lethal concentration

Figure 4. Applications of AgNPs in agriculture. Nonfertilizer enhanced plant growth and production. AgNPs also being utilized for production of transgenic varieties and crop protection. The AgNPs based Nano sensors helps in precise forming. They also proving helpful in promoting plant stress tolerances and soil improvement

Conclusion

Nanoparticles as emerging field have inspired many areas of our lives. Among various published method, biogenic synthesis (green synthesis) is more convenient and environment friendly. Out of many types of nano sized particles, AgNPs have gained remarkably significant importance. Because of their potential against microbes and diverse mode of action against bacterial cells, they are effectively being utilized as antimicrobial agents, even against MDR bacteria. They have diverse applications and are being successfully used in agricultural field, environment cleaning and disinfection, food industry and health sector. Alongside, they are being utilized successfully in lot of

biomedical applications including various surgeries, teeth filing material, bone cementing and many more. Furthermore, due to their easy synthesis and wider availability, AgNPs are being considered important constituents in the preparation of different commercially and bio-medically useful products. Therefore, it is concluded that AgNPs are promising particles from economical, commercial and industrial perspective. However, detailed and in depth study about the impact of AgNPs on human, animal and environment should be performed before mass scale field applications in various field of life.

Authors' contributions

Conceived and designed the experiments: I Liaquat, Analyzed the data: S Tufail & I

Liaqat, Contributed materials/ analysis/ tools: S Tufail & I Liaqat, Wrote the paper: S Tufail & I Liaqat.

Acknowledgments

We extend our thanks to all the research contributors to support and write this review article.

References

1. Cha KE & Myung H (2007). Cytotoxic Effects of Nanoparticles Assessed In Vitro and In Vivo. *J Microbiol Biotechnol* 17(9): 1573-1578.
2. Ahmed S, Ahmad M, Swami BL & Ikram S (2016). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise. *J Adv Res* 7(1): 17-28.
3. Kalliamurthi S, Selvaraj G, Çakmak ZE & Çakmak T (2016). Production and characterization of spherical thermostable silver nanoparticles from *Spirulina platensis* (Cyanophyceae). *Phycologia* 55(5): 568-576.
4. Satyavani K, Gurudeeban S & Ramanathan T (2014). Influence of leaf broth concentration of *Excoecaria agallocha* as a process variable in silver nanoparticles synthesis. *J Nanomed Res* 1(2): 11.
5. Borrego B, Lorenzo G, Mota-Morales JD, Almanza-Reyes H, Mateos F, López-Gil E, de la Losa N, Burmistrov VA, Pestryakov AN, Brun A & Bogdanchikova N (2016). Potential application of silver nanoparticles to control the infectivity of Rift Valley fever virus in vitro and in vivo. *Nanomed* 12(5): 1185-1192.
6. Benelli G (2016). Plant-mediated biosynthesis of nanoparticles as an emerging tool against mosquitoes of medical and veterinary importance: a review. *Parasitol Res* 115: 23-34.
7. Chari N, Felix L, Davoodbasha M, Ali AS & Nooruddin T (2017). In vitro and in vivo antibiofilm effect of copper nanoparticles against aquaculture pathogens. *Biocatal Agric Biotechnol* 10: 336-341.
8. LewisOscar F, MubarakAli D, Nithya C, Priyanka R, Gopinath V, Alharbi NS & Thajuddin N (2015). One pot synthesis and anti-biofilm potential of copper nanoparticles (CuNPs) against clinical strains of *Pseudomonas aeruginosa*. *Biofouling* 31: 379-391.
9. Christy AJ & Umadevi M (2012). Synthesis and characterization of monodispersed silver nanoparticles. *Adv Nat Sci-Nanosci* 3: 035013.
10. Siegel J, Kvítek O, Ulbrich P, Kolská Z, Slepíčka P & Švorčík V (2012). Progressive approach for metal nanoparticle synthesis. *Mater Lett* 89: 47-50.
11. Thakkar KN, Mhatre SS & Parikh RY (2010). Biological synthesis of metallic nanoparticles. *Nanomedicine* 6: 257-262.
12. Roy N, Gaur A, Jain A, Bhattacharya S & Rani V (2013). Green synthesis of silver nanoparticles: An approach to overcome toxicity. *Environ Toxicol Pharmacol* 36: 807-812.
13. Chouhan N, Ameta R & Meena RK (2017). Biogenic silver nanoparticles from *Trachyspermum ammi* (Ajwain) seeds extract for catalytic reduction of p-nitrophenol to p-aminophenol in excess of NaBH₄. *J Mol Liq* 230: 74-84.
14. Shedbalkar U, Singh R, Wadhwani S, Gaidhani S & Chopade BA (2014). Microbial synthesis of gold nanoparticles: current status and future prospects. *Adv Colloid Interface Sci* 209: 40-48.
15. He R, Qian X, Yin J & Zhu Z (2002). Preparation of polychrome silver nanoparticles in different solvents. *J Mater Chem* 12: 3783-3786.
16. Singh R, Wagh P, Wadhwani S, Gaidhani S, Kumbhar, A, Bellare J & Chopade BA (2013). Synthesis, optimization, and characterization of silver nanoparticles from *Acinetobacter calcoaceticus* and their enhanced antibacterial activity when combined with antibiotics. *Int J Nanomedicine* 8: 4277.

17. Sperling RA & Parak WJ (2010). Surface modification, functionalization and bioconjugation of colloidal inorganic nanoparticles. *Philosophical Transactions of the Royal Society A: Math Phys Eng Sci* 368(1915): 1333-1383.
18. Kraynov A & Müller TE (2011). Concepts for the stabilization of metal nanoparticles in ionic liquids. *App Ionic Liq Sci Technol* 12: 235-260.
19. Khan Z, Singh T, Hussain JI, Obaid AY, AL-Thabaiti SA & El-Mossalamy EH (2013). Starch-directed green synthesis, characterization and morphology of silver nanoparticles. *Colloids Surf B Biointerfaces* 102: 578-584.
20. Zhang XF, Liu ZG, Shen W & Gurunathan S (2016). Silver nanoparticles: synthesis, characterization, properties, applications and therapeutic approaches. *Int J Mol Sci* 17: 1534.
21. Talapko J, Matijević T, Juzbašić M, Antolović-Požgain A, Škrlec I (2020). Antibacterial Activity of Silver and Its Application in Dentistry, Cardiology and Dermatology. *Microorganisms* 8(9): 1400.
22. Jinu U, Jayalakshmi N, Anbu AS, Mahendran D, Sahi S & Venkatachalam P (2017). Biofabrication of cubic phase silver nanoparticles loaded with phytochemicals from *Solanum nigrum* leaf extracts for potential antibacterial, antibiofilm and antioxidant activities against MDR human pathogens. *J Clust Sci* 28: 489-505.
23. Zhang LL, Sun HB, Yang XL, Wen YW, Huang YH, Li M, Peng G, Tao HC, Ni SB & Liang G (2014). Study on electrochemical performance and mechanism of V-doped $\text{Li}_2\text{FeSiO}_4$ cathode material for Li-ion batteries. *Electrochim Acta* 152: 496–504.
24. Hoseinnejad M, Jafari SM & Katouzian I (2018). Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Crit Rev Microbiol* 44: 161-181.
25. Lara HH, Ayala-Núñez NV, Turrent LDCI & Padilla CR (2010). Bactericidal effect of silver nanoparticles against multidrug-resistant bacteria. *World J Microbiol Biotechnol* 26: 615-621.
26. Hindi KM, Ditto AJ, Panzner MJ, Medvetz DA, Han DS, Hovis CE, Hilliard JK, Taylor JB, Yun YH, Cannon CL & Youngs WJ (2009). The antimicrobial efficacy of sustained release silver–carbene complex-loaded L-tyrosine polyphosphate nanoparticles: Characterization, in vitro and in vivo studies. *Biomaterials* 30: 3771-3779.
27. Dakal TC, Kumar A, Majumdar RS & Yadav V (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Front Microbiol* 7: 1831.
28. Blecher K, Nasir A & Friedman A (2011). The growing role of nanotechnology in combating infectious disease. *Virulence* 2: 395-401.
29. Singh P, Pandit S, Garnæs J, Tunjic S, Mokkapati VR, Sultan A, Thygesen A, Mackevica A, Mateiu RV, Daugaard AE & Baun A (2018). Green synthesis of gold and silver nanoparticles from *Cannabis sativa* (industrial hemp) and their capacity for biofilm inhibition. *Int J Nanomedicine* 13: 3571.
30. Tang S & Zheng J (2018). Antibacterial activity of silver nanoparticles: structural effects. *Adv Healthc Mater* 7(13): 1701503.
31. Shahverdi AR, Fakhimi A, Shahverdi HR & Minaian S (2007). Synthesis and effect of silver nanoparticles on the antibacterial activity of different antibiotics against *Staphylococcus aureus* and *Escherichia coli*. *Nanomed Nanotechnol Biol Med* 3: 168-171.
32. Cui L, Chen P, Chen S, Yuan Z, Yu C, Ren B & Zhang K (2013). In situ study of the antibacterial activity and mechanism of action of silver

- nanoparticles by surface-enhanced Raman spectroscopy. *Anal Chem* 85: 5436-5443.
33. Li WR, Xie XB, Shi QS, Zeng HY, You-Sheng OY & Chen YB (2010). Antibacterial activity and mechanism of silver nanoparticles on *Escherichia coli*. *Appl Microbiol Biotechnol* 85: 1115-1122.
34. Kaweeteerawat C, Na Ubol P, Sangmuang S, Aueviriyavit S & Maniratanachote R (2017). Mechanisms of antibiotic resistance in bacteria mediated by silver nanoparticles. *J Toxicol Environ Health* 80: 1276-1289.
35. Wang L, Hu C & Shao L (2017). The antimicrobial activity of nanoparticles: present situation and prospects for the future. *Int J Nanomedicine* 12: 1227.
36. Paphitou NI (2013). Antimicrobial resistance: action to combat the rising microbial challenges. *Int J Antimicrob Agents* 42: S25-S28.
37. Tufail MS, Liaqat I, Mustafa G, Sattar M, Ibrahim S & Younas S (2021). Biosynthesis, Characterization and Antimicrobial activity of Silver Nanoparticles using culture supernatant of *Bacillus licheniformis* (MN900686). *Braz J Biol.*
38. Tufail MS, Liaqat I, Ibrahim S, Younas S, M.Tahir & A. Haleem (2021). Biogenic synthesis, characterization and antibacterial properties of silver nanoparticles against human pathogens: Characterization and antibacterial activity of biogenically synthesized AgNPs. *Braz J Biol.*
39. Morones-Ramirez JR, Winkler JA, Spina CS & Collins JJ (2013). Silver enhances antibiotic activity against gram-negative bacteria. *Sci Transl Med* 5: 190ra81-190ra81.
40. Xu H, Qu F, Xu H, Lai W, Wang YA, Aguilar ZP & Wei H (2012). Role of reactive oxygen species in the antibacterial mechanism of silver nanoparticles on *Escherichia coli* O157: H7. *Biomaterials* 25: 45-53.
41. Pelgrift RY & Friedman AJ (2013). Nanotechnology as a therapeutic tool to combat microbial resistance. *Adv Drug Deliv Rev* 65: 1803-1815.
42. Dilnawaz F, Acharya S, & Sahoo SK (2018). Recent trends of nanomedicinal approaches in clinics. *Int J Pharm* 538: 263-278.
43. Baelo A, Levato R, Julián E, Crespo A, Astola J, Gavalda J, Engel E, Mateos-Timoneda MA & Torrents E (2015). Disassembling bacterial extracellular matrix with DNase-coated nanoparticles to enhance antibiotic delivery in biofilm infections. *J Control Release* 209: 150-158.
44. Barapatre A, Aadil KR & Jha H (2016). Synergistic antibacterial and antibiofilm activity of silver nanoparticles biosynthesized by lignin-degrading fungus. *Bioresour Bioprocess* 3(1): 1-13.
45. Shahwany AW, Tawfeeq HK & Hamed SE (2016). Antibacterial and anti-biofilm activity of three phenolic plant extracts and silver nanoparticles on *Staphylococcus aureus* and *Klebsiella pneumoniae*. *J Biomed Biotechnol* 4: 12-18.
46. Khatoon N, Mishra A, Alam H, Manzoor N & Sardar M (2015). Biosynthesis, characterization, and antifungal activity of the silver nanoparticles against pathogenic *Candida* species. *Biol Nano Sci* 5: 65-74.
47. Alananbeh KM, Al-Refae WJ & Al-Qodah Z (2017). Antifungal effect of silver nanoparticles on selected fungi isolated from raw and waste water. *Ind J Pharma Sci* 79: 559-567.
48. Panáček A, Kolář M, Večeřová R, Prucek R, Soukupova J, Kryštof V, Hamal P, Zbořil R, & Kvítek L (2009). Antifungal activity of silver nanoparticles against *Candida* spp. *Biomaterials* 30: 6333-6340.
49. Al-Zubaidi S, Al-Ayafi A & Abdelkader H (2019). Biosynthesis, Characterization and Antifungal

- Activity of Silver Nanoparticles by *Aspergillus Niger* Isolate. *J Nanotech Res* 2: 022-035.
50. Hassan SA, Hanif E, Khan UH & Tanoli AK (2019). Antifungal activity of silver nanoparticles from *Aspergillus niger*. *Pak J Pharma Sci* 32.
 51. Lu L, Sun RW, Chen R, Hui CK, Ho CM, Luk JM, Lau GK & Che CM (2008). Silver nanoparticles inhibit hepatitis B virus replication. *Antivir Ther* 13: 253.
 52. Elechiguerra JL, Burt JL, Morones JR, Camacho-Bragado A, Gao X, Lara HH & Yacaman MJ (2005). Interaction of silver nanoparticles with HIV-1. *J nanobiotech* 3: 6.
 53. Jung JH, Hwang GB, Lee JE & Bae GN (2011). Preparation of airborne Ag/CNT hybrid nanoparticles using an aerosol process and their application to antimicrobial air filtration. *Langmuir* 27: 10256-10264.
 54. Fiorati A, Bellingeri A, Punta C, Corsi I & Venditti I (2021). Silver Nanoparticles for Water Pollution Monitoring and Treatments: Ecosafety Challenge and Cellulose-Based Hybrids Solution. *Polymers* 12(8): 1635.
 55. Asadi S & Moeinpour F (2019). Inactivation of *Escherichia coli* in water by silver-coated Ni 0.5 Zn 0.5 Fe₂O₄ magnetic nanocomposite: a Box–Behnken design optimization. *Appl Water Sci* 9: 23.
 56. Khaydarov RR, Khaydarov RA, Gapurova O, Garipov I & Firdaus M.L (2019). Silver nanoparticles as a biocide for water treatment applications. *Adv Res Nanosce Water Tech* 407-419.
 57. Chudasama B, Vala AK, Andhariya N, Upadhyay RV & Mehta RV (2009). Enhanced antibacterial activity of bifunctional Fe₃O₄-Ag core-shell nanostructures. *Nano Res* 2: 955-965.
 58. Mpenyana-Monyatsi L, Mthombeni NH, Onyango MS & Momba MN (2012). Cost-effective filter materials coated with silver nanoparticles for the removal of pathogenic bacteria in groundwater. *Int J Environ Res Pub Health* 9: 244-271.
 59. Kumar A, Vemula PK, Ajayan PM & John G (2008). Silver-nanoparticle-embedded antimicrobial paints based on vegetable oil. *Nat Mater* 7: 236-241.
 60. Gottesman R, Shukla S, Perkas N, Solovyov LA, Nitzan Y & Gedanken A (2011). Sonochemical coating of paper by microbiocidal silver nanoparticles. *Langmuir* 27: 720-726.
 61. Freeman AI, Halladay LJ & Cripps P (2012). The effect of silver impregnation of surgical scrub suits on surface bacterial contamination. *Vet J* 192: 489-493.
 62. Chung IM, Park I, Seung-Hyun K, Thiruvengadam M & Rajakumar G (2016). Plant-mediated synthesis of silver nanoparticles: their characteristic properties and therapeutic applications. *Nanoscale Res Lett* 11: 40.
 63. Abbasi E, Milani M, Fekri AS, Kouhi M, Akbarzadeh A, Tayefi NH, Nikasa P, Joo SW, Hanifehpour Y, Nejati-Koshki K & Samiei M (2016). Silver nanoparticles: synthesis methods, bio-applications and properties. *Crit Rev Microbiol* 42: 173-180.
 64. Wilkinson LJ, White RJ & Chipman JK (2011). Silver and nanoparticles of silver in wound dressings: a review of efficacy and safety. *J Wound Care* 20: 543-549.
 65. Yang Y & Hu H (2015). A review on antimicrobial silver absorbent wound dressings applied to exuding wounds. *J Microb Biochem Technol* 7: 228-233.
 66. Larese FF, D'Agostin F, Crosera M, Adami G, Renzi N, Bovenzi M & Maina G (2009). Human skin penetration of silver nanoparticles through intact and damaged skin. *Toxicol* 255: 33-37.
 67. Kumar SSD, Rajendran NK, Houreld NN & Abrahamse H (2018). Recent advances on silver nanoparticle and biopolymer-based biomaterials for

- wound healing applications. *Int J Biol Macromol* 115: 165-175.
68. Bozaci E, Akar E, Ozdogan E, Demir A, Altinisik A & Seki Y (2015). Application of carboxymethylcellulose hydrogel based silver nanocomposites on cotton fabrics for antibacterial property. *Carbohydr Polym* 134: 128-135.
 69. Emam HE, Saleh NH, Nagy KS & Zahran MK (2015). Functionalization of medical cotton by direct incorporation of silver nanoparticles. *Int J Biol Macromol* 78: 249-256.
 70. Correia TR, Figueira DR, de Sá KD, Miguel SP, Fradique RG, Mendonça AG & Correia IJ (2016). 3D printed scaffolds with bactericidal activity aimed for bone tissue regeneration. *Int J Biol Macromol* 93: 1432-1445.
 71. Castiglioni S, Cazzaniga A, Locatelli L & Maier JA (2017). Silver nanoparticles in orthopedic applications: New insights on their effects on osteogenic cells. *Nanomaterials* 7: 124.
 72. Lu H, Liu Y, Guo J, Wu H, Wang J & Wu G (2016). Biomaterials with antibacterial and osteoinductive properties to repair infected bone defects. *Int J Mol Sci* 17: 334.
 73. Albers CE, Hofstetter W, Siebenrock KA, Landmann R & Klenke FM (2013). In vitro cytotoxicity of silver nanoparticles on osteoblasts and osteoclasts at antibacterial concentrations. *Nanotoxicol* 7: 30-36.
 74. Zhou K, Dong C, Zhang X, Shi L, Chen Z, Xu Y & Cai H (2015). Preparation and characterization of nanosilver-doped porous hydroxyapatite scaffolds. *Ceram Int* 41: 1671-1676.
 75. Rupp M.E, Fitzgerald T, Marion N, Helget V, Puumala S, Anderson JR & Fey PD (2004). Effect of silver-coated urinary catheters: efficacy, cost-effectiveness, and antimicrobial resistance. *Am J Infect Control* 32: 445-450.
 76. Roe D, Karandikar B, Bonn-Savage N, Gibbins B & Rouillet JB (2008). Antimicrobial surface functionalization of plastic catheters by silver nanoparticles. *J Antimicrob Chemo* 61: 869-876.
 77. Cheng L, Weir MD, Xu HH, Antonucci JM, Lin NJ, Lin-Gibson S, Xu SM & Zhou X (2012). Effect of amorphous calcium phosphate and silver nanocomposites on dental plaque microcosm biofilms. *J Biomed Mater Res* 100: 1378-1386.
 78. Magalhães APR, Santos LB, Lopes LG, Estrela CRDA, Estrela C, Torres ÉM, Bakuzis AF, Cardoso PC & Carrião MS (2012). Nanosilver application in dental cements. *ISRN Nanotechnology* 2012.
 79. Palmer WE, Bromley PT & Brandenburg RL (2007). Wildlife & pesticides-peanuts. *NCCES* 21-28.
 80. Gnanadesigan M, Anand M, Ravikumar S, Maruthupandy M, Vijayakumar V, Selvam, S, Dhineshkumar M & Kumaraguru AK (2011). Biosynthesis of silver nanoparticles by using mangrove plant extract and their potential mosquito larvicidal property. *Asian Pac J Trop Med* 4: 799-803.
 81. Zahir AA, Bagavan A, Kamaraj C, Elango G & Rahuman AA (2012). Efficacy of plant-mediated synthesized silver nanoparticles against *Sitophilus oryzae*. *J Biopestici* 5: 95.
 82. Khodakovskaya MV, De Silva K, Biris AS, Dervishi E & Villagarcia H (2012). Carbon nanotubes induce growth enhancement of tobacco cells. *ACS nano* 6: 2128-2135.
 83. Shang Y, Hasan M, Ahammed GJ, Li M, Yin H & Zhou J (2019). Applications of nanotechnology in plant growth and crop protection: a review. *Mol* 24: 2558.
 84. Benn TM & Westerhoff P (2008). Nanoparticle silver released into water from commercially available sock fabrics. *Environ Sci Technol* 42: 4133-4139.

85. AshaRani PV, Low Kah Mun G, Hande MP & Valiyaveetil S (2009). Cytotoxicity and genotoxicity of silver nanoparticles in human cells. *ACS nano* 3: 279-290.
86. Sanpui P, Chattopadhyay A & Ghosh SS (2011). Induction of apoptosis in cancer cells at low silver nanoparticle concentrations using chitosan nanocarrier. *ACS Appl Mater Interfaces* 3: 218-228.
87. Carbone M, Donia DT, Sabbatella G & Antiochia R (2016). Silver nanoparticles in polymeric matrices for fresh food packaging. *J King Saud Uni Sci* 28: 273-279.
88. Tavakoli H, Rastegar H, Taherian M, Samadi M & Rostami H (2017). The effect of nano-silver packaging in increasing the shelf life of nuts: An in vitro model *Ital J Food Saf* 6(4).
89. An J, Zhang M, Wang S & Tang J (2008). Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. *LWT-Food Sci Technol* 41: 1100-1107.
90. Mohammed Fayaz A, Balaji K, Girilal M, Kalaichelvan PT & Venkatesan R (2009). Mycobased synthesis of silver nanoparticles and their incorporation into sodium alginate films for vegetable and fruit preservation. *J Agric Food Chem* 57: 6246-6252.
91. Mahdi SS, Vadood R & Nourdahr R (2012). Study on the antimicrobial effect of nanosilver tray packaging of minced beef at refrigerator temperature. *Global Vet* 9(3): 284-289.
92. Yang H, Song T, Liu L, Devadoss A, Xia F, Han H, Park H, Sigmund W, Kwon K & Paik U (2013). Polyaniline/polyoxometalate hybrid nanofibers as cathode for lithium ion batteries with improved lithium storage capacity. *J Phys Chem C* 117: 17376-17381.
93. Karimi-Maleh H, Sanati AL, Gupta VK, Yoosefian M, Asif M & Bahari A (2014). A voltammetric biosensor based on ionic liquid/ NiO nanoparticle modified carbon paste electrode for the determination of nicotinamide adenine dinucleotide (NADH). *Sens Actuators B* 204: 647-654.
94. Najafi M, Khalilzadeh M A & Karimi-Maleh H (2014). A new strategy for determination of bisphenol A in the presence of Sudan I using a ZnO/CNTs/ionic liquid paste electrode in food samples. *Food Chem* 158: 125-131.
95. Chen D, Mei X, Ji G, Lu M, Xie J, Lu J & Lee JY (2012). Reversible lithium-ion storage in silver-treated nanoscale hollow porous silicon particles. *Angew Chem* 124(10): 2459-2463
96. Pan L, Liu YT, Xie XM & Zhu XD (2014). Coordination-driven hierarchical assembly of silver nanoparticles on MoS₂ nanosheets for improved lithium storage. *Chem Asian J* 9: 1519-1524
97. Yola ML, Gupta VK, Eren T, Şen AE & Atar N (2014). A novel electro analytical nanosensor based on graphene oxide/silver nanoparticles for simultaneous determination of quercetin and morin. *Electrochim Acta* 120: 204-211.
98. Gupta VK, Yola ML, Eren T, Kartal F, Çağlayan MO & Atar N (2014). Catalytic activity of Fe@Ag nanoparticle involved calcium alginate beads for the reduction of nitrophenols. *J Mol Liq* 190: 133-138.