RESEARCH ARTICLE

Evaluation of physical, chemical and biological properties of silver nanoparticles and their synthesis and applications

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ABSTRACT

Silver nanoparticles are one of the most famous and widely used nanotechnology products, it is estimated that nearly 320 tons of silver nanoparticles are used in the world every year and this widespread use causes it to eventually become a pollutant of the soil and the environment, this pollution can occur indirectly by entering the environment or directly by agricultural activities. A detailed study of the physical, chemical and biological properties of silver nanoparticles and their synthesis and applications is necessary, because the physicochemical properties of a particle can have a significant effect on its biological properties. The findings of the present study clearly showed that synthesize of silver nanoparticles with defined size and morphology under optimal conditions is possible via an eco-friendly approach. The findings revealed that silver nanoparticles produced by the green synthesis method, in spite of good antibacterial activity cause negligible cytotoxicity and the toxic effects of silver nanoparticles synthesized by physical and chemical methods are inevitable compared to biological synthesis methods. So far, a few studies have been done on the toxicity of silver nanoparticles and findings of the present study showed that the final studies on determining the toxicity of silver nanoparticles are not sufficient because their toxicity depends on many factors such as their concentration, size, shape and surface. Also sources, the route of entry, toxicological evaluation methods and dose units may vary significantly hence it is difficult to determine the exact range of toxicity of silver nanoparticles.

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INTRODUCTION

Silver nanoparticles are one of the most famous and widely used nanotechnology products, it is estimated that nearly 320 tons of silver nanoparticles are used in the world every year (Nowack et al. 2011). This widespread use causes it to eventually become a pollutant of the soil and the environment, this pollution can occur indirectly by entering the environment or directly by agricultural activities (Zhang et al. 2012). Apart from primary medical applications, silver nanoparticles are also used in domestic, industrial and agricultural applications such as: water purification, plant growth and textile cleaning (Pareek et al. 2018; Hänsch and Emmerling, 2010). In the last decade, the volume of production and the fields of application of silver nanoparticles have increased due to its unique characteristics such as: high surface-to-volume ratio, high chemical reactivity and optical properties (Sun et al. 2017; Abbasi et al. 2016). Silver nanoparticles can undergo various physico-chemical transformations such as: oxidation, aggregation, dissolution, complex and secondary reactions. These developments, in turn, affect the mechanism as well as the bioavailability of silver nanoparticles and cause the toxicity of silver nanoparticles (Masrahi et al. 2014).

EXPERIMENTAL

Analysis of silver nanoparticles

Accurate description of silver nanoparticles is necessary, because the physicochemical properties of a particle can have a significant effect on its biological properties, the biological activity of silver nanoparticles depends on factors such as surface chemistry, size, size distribution, shape, particle morphology, particle composition, coverage, aggregation and dissolution rate, particle reactivity in solution, ion diffusion efficiency and cell type (Gliga et al. 2014). Therefore, the development of silver nanoparticles with controlled structures that are uniform in terms of size, morphology and performance is necessary for various applications (Sriram et al. 2010).

Properties of silver nanoparticles

Today, extensive strategies are available to modify the surface chemistry of various nanoparticles; these engineered silver nanoparticles have different optical, electrical, magnetic, chemical, and mechanical properties due to the higher surface-to-volume ratio of the material, while decreasing the size. They increase and ultimately lead to an increase in the absorption of environmental atoms and changes in the properties and behavior of materials, which begin to obey quantum mechanical laws as soon as the size of the particles decreases significantly (Carbone et al. 2014).

Physical properties of silver nanoparticles

Physical characteristics of silver nanoparticles such as size, shape, size distribution, surface area, etc. should be considered before evaluating toxicity or biocompatibility (Lin et al. 2014).

Smaller sized particles can cause more toxicity than larger particles because they have a larger surface area (Sriram et al. 2012). Shape is equally important in determining toxicity (Stoehr et al. 2011). For example, in the field of biomedicine, a variety of nanostructures have been used, including: nanocubes, nanoplates, nanorods, spherical, flower-like nanoparticles, etc. (Wei et al. 2015). The atomic density of silver affects its shape, rod or plate nanoparticles have more antibacterial activity compared to shapes (spherical, triangular, etc.) due to higher atomic density (Pareek et al. 2018). The toxicity of silver nanoparticles mainly depends on the coatings on the surface of the nanoparticles and its availability with chemical or biological substances. The surface charges of silver nanoparticles can determine their toxic effect in cells, for example: the positive surface charge of these nanoparticles makes them more suitable and allows them to be available for a long time compared to nano negatively charged particles (Schlinkert et al. 2015). What makes a toxic nanomaterial so far has not been simply defined, current knowledge shows that it largely depends on the physical properties of the nanoparticles, on the properties of the nanomaterials themselves, in particular their size, composition and surface function (Krug and Wick. 2011). As mentioned, silver nanoparticles exhibit their intrinsic antimicrobial activity through a variety of mechanisms they give (Dakal et al. 2016).

Chemical properties of silver nanoparticles

The chemical characteristics of silver nanoparticles include: the speed of dissolution of ions, oxidation potential, etc. It is silver particles, because the ionic form of silver has a greater toxic potential than silver nanoparticles (McQuillan and Shaw. 2014). It is predicted that the release of silver ions from the core of silver nanoparticles is the ultimate basis of the bactericidal activity of silver nanoparticles (Panáček et al. 2018). The surface coating also has a great effect on the kinetics of ion release from silver nanoparticles (Pareek et al. 2018).

When bacteria are exposed to silver nanoparticles, due to the formation of peroxide, superoxide and free hydroxyl ions, they experience a high level of oxidative stress, which ultimately leads to the inactivation of the bacterial cell (Reidy et al. 2013).

Biological properties of silver nanoparticles

Most studies have shown that different metals cause distinct damages to microbial cells, which include cell wall, and membrane damage, oxidative stress, protein dysfunction, and cell damage (Lemire et al. 2013). Nanomedicine is rapidly advancing, and there is a fine line between the use of innovative medical tools and the careless exposure to the use of nanomaterials that are potentially harmful to human health and the environment (Ebrahimzadeh et al. 2018). While enjoying silver nanoparticles as an option to deal with diseases, one should pay attention to the fact that the same treatment technique can also produce dangerous and unpleasant results, silver nanoparticles are toxic substances and there is still a device to determine nontoxicity. No, since silver nanoparticles have become a major drug to fight diseases such as cancer, anti-angiogenic effects in the retina, etc., researchers plan to develop silver nanoparticles that, in addition to reducing the adverse effects of toxicity include the main feature at a reasonable cost (Ebrahimzadeh et al. 2018). The biological activity of silver nanoparticles depends on the morphology and control of the size and shape of the structure of silver nanoparticles, as far as the size and shape of silver nanoparticles are concerned, the smaller the size and the shorter the triangular shape of the nanoparticles, the more effective it is and the superior properties (Zhang et al. 2016). Silver nanoparticles increase the bioavailability of therapeutic agents after systemic and local administration (Jo et al. 2015). On the other hand, it can affect cellular absorption, biological distribution, penetration into biological barriers and resulting therapeutic effects (Duan and Li. 2013). Therefore, the development of silver nanoparticles with controlled structures that are uniform in size, morphology, and functionality is essential for various biomedical applications (Zhang et al. 2016). Silver nanoparticles are one of the most widely used antimicrobial metal nanoparticles in today's era due to their inherent characteristics and extensive bactericidal effects against gram-negative and gram-positive bacteria (Shao et al. 2018). Currently, silver nanoparticles with their inherent anti-bacterial and anti-inflammatory effects are used in dressing wounds and burns, as well as in various pharmaceutical formulations such as: ointments, antibacterial clothing and medical equipment coatings (López-Esparza et al. 2016).

Synthesis methods of silver nanoparticles

The synthesis of silver nanoparticles is carried out by two methods (top-down) and (bottom-up), the term (top-down) refers to the synthesis of nanoparticles from bulk by physical processes, the (bottom-up) approach to the formation of nanoparticles refers to the constituent atoms by chemical processes, biological methods of silver nanoparticle syntheses are used as an alternative to physical and chemical methods and using microorganisms (algae, fungi, yeasts, bacteria and viruses), enzymes and plants (plant extracts) are done (Zhu et al. 2020).

Physical method of synthesis of silver nanoparticles

Evaporation, condensation and laser ablation are the most important physical approaches, the absence of solvent contamination in the prepared thin layers and the uniformity of the distribution of silver nanoparticles is one of the advantages of physical synthesis methods compared to chemical processes, high consumption of electrical energy, occupying space a lot and spending a lot of time to achieve thermal stability is one of the disadvantages of the physical synthesis method of silver nanoparticles (Iravani et al. 2014).

Chemical method of synthesis of silver nanoparticles

The most popular chemical methods for the synthesis of silver nanoparticles include: chemical reduction using a variety of organic and inorganic reducing agents, electrochemical techniques, physicochemical reduction and radiolysis, which are widely used, among the mentioned methods, the most common method for nano synthesis of silver particles are chemically reduced by organic and inorganic reducing agents, generally different reducing agents such as sodium citrate, ascorbate, sodium borohydride, hydrazine and hydroquinone are used in this method (Iravani et al. 2014). Most of these methods are still in the development stage and face practical problems such as stability and accumulation of nanoparticles, control of crystal growth, morphology, size and size distribution, extraction and purification of produced nanoparticles, the advantages of silver nanoparticles synthesis by chemical methods: ease of production, low cost and high efficiency (Gurunathan et al. 2015).

Biological method of synthesis of silver nanoparticles

To overcome the shortcomings of chemical methods, biological methods of silver nanoparticle synthesis have appeared as suitable options, recently, the synthesis of silver nanoparticles is a simple and cost-effective approach using different biological systems, including: bacteria, fungi and plants, therefore it is important to identify the biological properties of silver nanoparticles in order to evaluate the functional aspects of the synthesized particles, extracts and small biomolecules, such as vitamins and amino acids as an alternative method for chemicals are used not only for the synthesis of silver nanoparticles, but also for the synthesis of several other nanoparticles such as gold and graphene (Gurunathan et al. 2015). Gram-negative and gram-positive bacteria are indicators for the synthesis of silver nanoparticles, the main advantage of biological synthesis methods is the availability of amino acids, proteins or secondary metabolites, it seems that controlling the size and shape of the particles in the method of biological synthesis of silver nanoparticles is an important factor for various biomedical applications (Gurunathan et al. 2014). By using bacterial proteins or plant extracts as reducing agents, the shape, size and distribution of silver nanoparticles can be controlled (Zhang et al. 2016). Other advantages of the biological synthesis methods of silver nanoparticles include the availability of a wide range of biological sources, shortening of time, high density, stability and solubility of prepared silver nanoparticles in water (Zhang et al. 2016). In the method of biological synthesis of silver nanoparticles, extracts of biological agents such as: microbes and plants can be used as a reducing or protective agent to make silver nanoparticles, in these extracts there are various combinations of biological molecules that have reducing potential, such as: Amino acids, Vitamins, Proteins, Enzymes and Polysaccharides are found (Keat et al. 2015).

Applications of silver nanoparticles

Due to the unique properties of silver nanoparticles, they are used for several applications including antibacterial agents, in industrial, household and healthcare-related products, in consumer products, coating medical devices, optical sensors and cosmetics. They have been used in the pharmaceutical industry, in the food industry, in diagnostics, in orthopedics, drug delivery, as anti-cancer agents, and finally, they have increased the tumor-killing effects of anti-cancer drugs (Chernousova and Epple. 2013). Recently, silver nanoparticles have been repeatedly used in many textiles, keyboards, wound dressings and biomedical devices (Li et al. 2017). Silver nanoparticles can change the regulation of more than 1000 genes, among several genes, metallothionein, heat shock protein and H\histones were notable (Foldbjerg et al. 2012). Recently, autophagy-induced cell death has been another identified mechanism for the anticancer activity of silver nanoparticles. Nanoparticle-induced autophagy is a critical cellular degradation process, and increased autophagy can cause cell death (Lin et al. 2014). The ability of silver nanoparticles in cellular imaging can be used to study inflammation, tumors, immune response and the effects of stem cell therapy. Silver plays an important role in imaging systems due to its stronger and clearer plasmon resonance. Because of their smaller size, silver nanoparticles are mainly used in diagnosis, treatment, as well as combination therapy and diagnostic approaches, which ultimately lead to increased brightness and clearer imaging (Meyers and Cottone. 2013). Nano silver has been intensively used in several applications, including diagnosis, cancer treatment, and as a drug carrier (Ge et al. 2014). Silver nanoparticles in combination with vanadium oxide have been used in battery cell components to improve battery performance in implantable medical devices (Etheridge et al. 2013).

RESULTS AND DISCUSSIONS

RESULTS

Today, there is a need to develop eco-friendly processes, which do not use toxic chemicals in the synthesis. The biological synthesis methods of silver nanoparticles are an important field of modern research dealing with design and biosynthesis of particle structures ranging from approximately 1-100 nm. For the green synthesis of silver nanoparticles it is necessary to take plant extracts as a reducing agent and use plant extracts taken from the bark, stems, roots, leaves, flowers, oil, fruit peels and seeds, Table (1).

The findings of the present study clearly showed that can synthesize silver nanoparticles with defined size and morphology under optimal conditions and with an eco-friendly approach, Table (1). The findings revealed that silver nanoparticles produced by the green synthesis method, in spite of good antibacterial activity, cause negligible cytotoxicity. Create green the biological synthesis of silver nanoparticles does not require high temperature or toxic and dangerous additives, but the biological agents used must be carefully selected, Tables (2) and (3).

DISCUSSION

Although silver nanoparticles play an important role in clinical research, several factors such as: raw materials, synthesis method, stability, bio distribution, controlled release, and aggregation, cell-specific targeting and finally toxicological issues must be considered. A detailed study of the physical, chemical and biological properties of silver nanoparticles and their synthesis and applications is necessary, because the physicochemical properties of a particle can have a significant effect on its biological properties; this step is just as important as the synthesis approach. Nano-sized metal particles are unique and due to their surface-to-volume ratio, they can significantly change physical, chemical, and biological properties, for this reason, these nanoparticles have been exploited for various purposes (Zhang et al. 2016).

Metal nanoparticles based on their size and characteristics, have unique properties such as surface expansion, pore size, charge density on the surface, cylindrical and spherical shape, color, amorphous and crystalline structures. Environmental factors such as air, heat, sunlight and humidity affect the properties of nanoparticles. Energy sources such as light, heat, electricity, sound and short energy waves are used in the synthesis process of silver nanoparticles. In addition to the types of precursor salts, additives such as reducing agents, coating agents and stabilizers are used with the expected size and shape, and reaction parameters such as reaction temperature, time, pH and additional energy sources are used in the process. The production of silver nanoparticles is considered. Physical and chemical methods of silver nanoparticles synthesis seem very expensive and dangerous. Silver nanoparticles produced by biological synthesis method have high performance, solubility and stability (Gurunathan et al. 2015).

The green material or entity used for the production would substantially define the physical and chemical properties and as a consequence, the biological activities of the obtained nanomaterials (Rónavári et al. 2021). After the green material is selected, and its active ingredients have been regarded, all other chemicals required for nanoparticle synthesis should be attentively picked to preferentially utilize biocompatible substances and to avoid toxic chemicals (Rónavári et al. 2021).

CONCLUSION

The preferred synthesis method of silver nanoparticles is green synthesis, because it is eco-friendly, simple process, low cost, reproducible and requires a small amount of energy. In nanochemistry, the size of the particles is the most critical factor, and by using different plants, you can get nanoparticles of different sizes from the same metal. It has been clearly seen that different plants have different capabilities in reducing metal ions. Therefore, the only disadvantage of the green synthesis method is the production of smaller amounts of silver nanoparticles. The toxic effects of silver nanoparticles synthesized by physical and chemical methods are inevitable compared to biological synthesis methods. To ensure the biological safety of using silver nanoparticles in humans, studies related to the biocompatibility of silver nanoparticles and their interaction with cells and tissues should be done, and biological applications based on nanotechnology must be safe, reliable, and durable. So far, a few studies have been done on the toxicity of silver nanoparticles and the findings of the present study showed that the final studies on determining the toxicity of silver nanoparticles are not sufficient because their toxicity depends on many factors such as their concentration, size, shape and surface. Also sources, route of entry, toxicological evaluation methods and dosage units may vary considerably; hence it is difficult to determine the exact range of toxicity of silver nanoparticles.

Table (1). Synthesis of silver nanoparticles by intermediary plants

Precursor	Intermediary Plants	Size of Silver Nanoparticles (nm)
Silver Nitrate	Mentha peprita	90
Silver Nitrate	Tribulus terrestris	16–28
Silver Nitrate	Nyctanthes arbor-tristis	50–80
Silver Nitrate	Azadirachta indica	50–100
Silver Nitrate	Pelargonium sidoides	16–40
Silver Nitrate	Vigna unguiculata	24.35
Silver Nitrate	Cinnamomum camphora	55–80
Silver Nitrate	Aloe barbadensis miller	15.2 ± 4.2
Silver Nitrate	Amaranthus retroflexus	10–32
Silver Nitrate	Artocarpus heterophyllus lam	10.78
Silver Nitrate	Prunus yedoensis	20–70
Silver Nitrate	Morinda citrifolia	30–55
Silver Nitrate	Bunium persicum	20–50
Silver Nitrate	Justicia adhatoda	25
Silver Nitrate	Adenium obesum	10–30
Silver Nitrate	Coffee arabica	20–30
Silver Nitrate	Vigna radiata	5–30
Silver Nitrate	Jatropha curcas	10–20
Silver Nitrate	Lantana camara	14–27
Silver Nitrate	Sesuvium portulacastrum	5–20

Table (2). Synthesis of silver nanoparticles by intermediary bacteria

Precursor	Intermediary Bacteria for Green Synthesis	Size of Silver Nanoparticles (nm)
Silver Nitrate	Klebsiella pneumonia	1–6
Silver Nitrate	Deinococcus radiodurans	4–50
Silver Nitrate	Bacillus subtilis	20–50
Silver Nitrate	Serratia nematodiphila	10–31
Silver Nitrate	Nocardiopsis	45 ± 0.15
Silver Nitrate	Pseudomonas (proteolytic, meridiana)	6–13
Silver Nitrate	Bacillus licheniformis	18–63
Silver Nitrate	Bacillus pumilus	77–92
Silver Nitrate	Gluconacetobacter xylinus	40–100

Table (3). Synthesis of silver nanoparticles by intermediary fungi

Precursor	Intermediary Fungi for Green Synthesis	Size of Silver Nanoparticles (nm)
Silver Nitrate	Amylomyces rouxii	5–27
Silver Nitrate	Aspergillus niger	3–30
Silver Nitrate	Alternaria alternate	20–60
Silver Nitrate	Aspergillus fumigatus	5–25
Silver Nitrate	Rhizopus stolonifer	9.47
Silver Nitrate	Cladosporium sphaerospermum	15.1 ± 1.0
Silver Nitrate	Fusarium oxysporum	5–15
Silver Nitrate	Pestalotiopsis microspore	5–25
Silver Nitrate	Phanerochaete chrysosporium	50–200
Silver Nitrate	Cochliobolus lunatus	3–21
Silver Nitrate	Aspergillus terreus	6–100
Silver Nitrate	Penicillium expansum	14–76

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest. The authors are responsible for the content and writing of this article

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