Review Article ISSN:2456-1622

Asia Pacific Journal of
Pharmaceutical and Applied Sciences

GREEN SYNTHESIZED SILVER NANOPARTICLES: BIOMEDICAL APPLICATIONS AND SYNTHESIS METHODS

Sunder Bhati[1], Azharuddin[1]
[1]Department of Pharmaceutics, Lords University, Alwar, Rajasthan, India

ABSTRACT

Green synthesis of silver nanoparticles (AgNPs) has emerged as an eco-friendly, cost-effective, and sustainable alternative to conventional physical and chemical synthesis methods. The present review highlights the mechanistic aspects, characterization techniques, and diverse biomedical applications of green synthesized silver nanoparticles. Plant extracts, microorganisms, and other biological materials act as reducing and stabilizing agents during nanoparticle formation, eliminating the need for toxic chemicals and harsh reaction conditions. The synthesis process is influenced by various factors such as pH, temperature, concentration, and reaction time, which significantly affect nanoparticle size, morphology, and stability. Mechanistically, phytochemicals including flavonoids, phenolics, alkaloids, proteins, and terpenoids play a crucial role in the bioreduction of silver ions and stabilization of nanoparticles. Characterization of AgNPs is commonly performed using techniques such as UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Dynamic Light Scattering (DLS). Green synthesized AgNPs exhibit remarkable biological activities including antimicrobial, antioxidant, anti-inflammatory, anticancer, antiviral, wound healing, and drug delivery potential. Their broad-spectrum activity against multidrug-resistant pathogens further enhances their biomedical significance. Overall, green synthesized silver nanoparticles represent a promising nanotechnological platform for future therapeutic and pharmaceutical applications with improved biocompatibility and reduced environmental toxicity.

Keywords: Silver nanoparticles, Green synthesis, Biosynthesis, Nanotechnology, Antimicrobial activity, Biomedical applications, Cytotoxicity, Nanoparticle characterization, Drug delivery

Submitted: 13 March 2026; Revised: 27 March 2026; Accepted: 28 April 2026

INTRODUCTION

Nanoparticles are ultrafine materials with dimensions typically ranging from 1 to 100 nm. Due to their nanoscale size, they exhibit distinctive physical, chemical, and biological properties that differ significantly from those of bulk materials. Their exceptionally high surface-area-to-volume ratio and reduced particle size contribute to enhanced reactivity, improved surface interactions, and unique functional characteristics. Owing to these remarkable properties, nanoparticles have found widespread applications in diverse fields such as medicine, pharmaceuticals, biotechnology, electronics, environmental science, and material engineering [1].

There are several types of Nanoparticles currently being investigated for a wide range of biomedical, pharmaceutical, industrial, and environmental applications. Among them, Silver Nanoparticles have attracted considerable scientific interest because of their remarkable biological activities, particularly their potent antimicrobial properties. Silver nanoparticles exhibit broad-spectrum bactericidal, fungicidal, and virucidal activities, making them highly effective against numerous pathogenic microorganisms [2].

Although the exact antimicrobial mechanism of silver nanoparticles has not been fully elucidated, several mechanisms have been proposed. The primary mechanism involves the release of silver ions (Ag^+), which interact with microbial cell membranes, disrupt membrane permeability, alter cellular respiration, and induce structural damage. Furthermore, silver nanoparticles stimulate the generation of reactive oxygen species (ROS), leading to oxidative stress, protein denaturation, DNA damage, and eventual microbial cell death [3]. Due to these multiple modes of action, silver nanoparticles demonstrate effectiveness against a broad spectrum of pathogens, including antibiotic-resistant and multidrug-resistant microorganisms.

The unique physicochemical and biological properties of silver nanoparticles have enabled their application in numerous fields. Their antimicrobial potential has been extensively utilized in agriculture, wound healing, medical coatings, and dental applications [4–6]. In addition, the ability of silver nanoparticles to penetrate cellular membranes and exhibit intracellular activity has expanded their applications in anticancer therapy, targeted drug delivery, and bioimaging technologies [7].

Nanoparticles (NPs) have emerged as one of the most extensively investigated materials in contemporary scientific research. According to data from the Web of Science Core Collection, more than 500,000 publications, including research articles and patents, have been reported over the past five years [8]. Among these, approximately 54,070 publications are specifically related to silver nanoparticles (AgNPs), representing nearly 10% of the total literature in the field of nanomaterials. Recent studies on AgNPs have primarily focused on diverse synthesis strategies, antimicrobial applications, drug delivery systems, and toxicological evaluations. In particular, green synthesis approaches have gained substantial attention due to their eco-friendly nature and potential to minimize the adverse environmental and biological effects associated with conventionally synthesized AgNPs. Considering the growing scientific interest and significant advancements in this area, the present review aims to comprehensively summarize the recent progress in silver nanoparticle research, with special emphasis on green synthesis methods, biomedical applications, and safety considerations.

Properties of Silver Nanoparticles

Reflecting typical NP traits, silver NPs exhibit distinct physical and chemical properties due to their small size and high surface-area-to-volume ratio [9]. These properties include high electrical and thermal conductivity, antibacterial activity, and optical characteristics, which mainly depend on their shape, size, surface chemistry, composition, coating, and agglomeration [10].

In line with that, the synthesis method is also essential in defining the characteristics of silver NPs. For instance, both the advantages and disadvantages of silver NP synthesis methods through physical, chemical, and biological approaches were demonstrated in a recent review [11]. Moreover, compared to other types of metals, silver NPs exhibit stable and chemically less reactive characteristics. These properties make them remarkable agents for many biological applications, including antibacterial coatings, biosensors, bioimaging, wound healing, diabetes treatment, and cancer therapy [12]. Properties of silver NPs are also related to their toxicity potential, which has been extensively discussed in the current literature [13]. Nevertheless, detailed examples of these negative effects, including their mechanisms and potential health risks, will be discussed in the toxicity section.

In this section, we have explored the diverse properties of silver NPs and their significance in various disciplines. From their exceptional antibacterial activities to enhanced optical traits, silver NPs have been included in much innovative research and many applications. Regarding the current research background, this section aims to provide a comprehensive understanding of how silver NPs contribute to advances in nanotechnology with their unique characteristics.

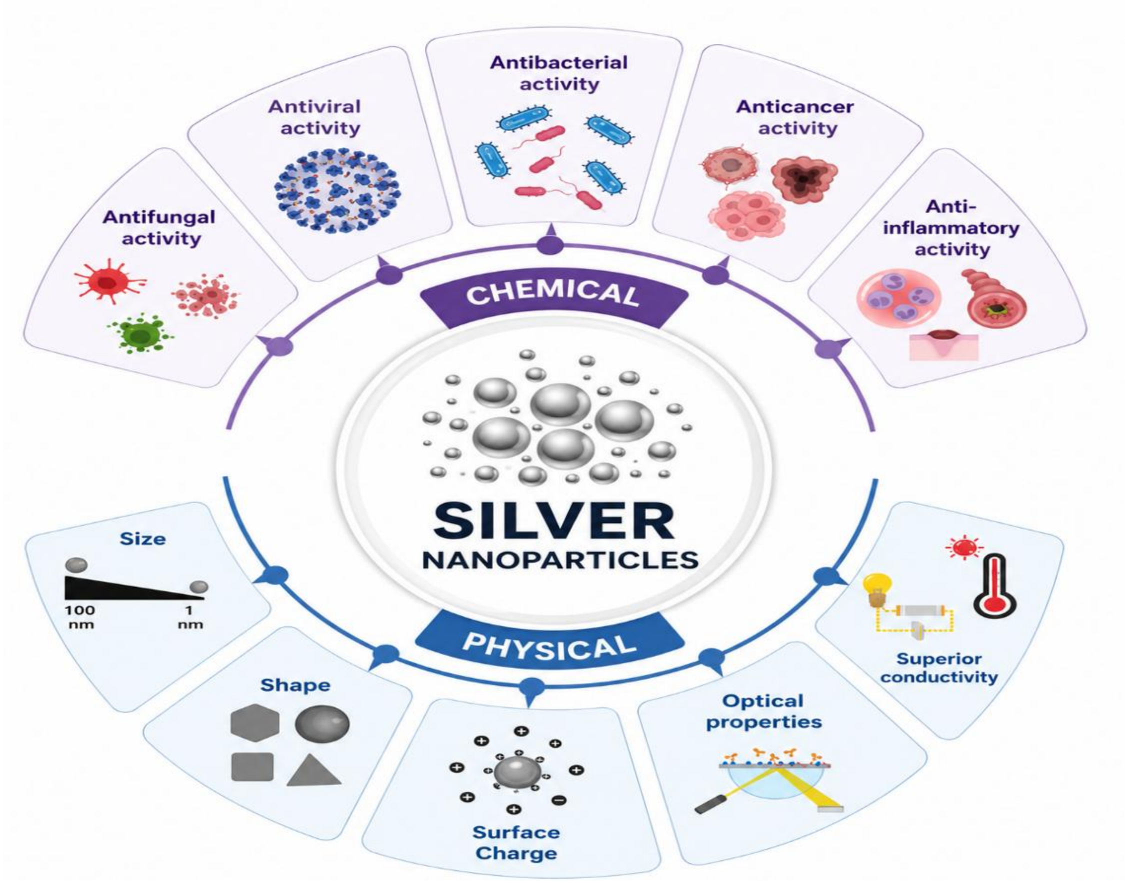

Figure 1. Properties of Silver Nanoparticles

Synthesis of Silver Nanoparticles

Physical Methods

Among the various physical techniques used for the preparation of silver nanoparticles (AgNPs), evaporation–condensation and laser ablation are considered the most widely applied approaches. Compared with chemical methods, physical techniques offer advantages such as the absence of solvent contamination and the production of nanoparticles with a more uniform distribution. However, conventional physical synthesis using a tube furnace under atmospheric conditions presents several limitations. These include high energy consumption, large equipment size, prolonged heating periods to attain thermal equilibrium, and an increase in the surrounding environmental temperature. Typically, tube furnaces require several kilowatts of power and long preheating durations before reaching stable operational conditions [14,15].

To overcome these drawbacks, researchers developed a method employing a compact ceramic heater with a localized heating zone for silver nanoparticle synthesis. In this process, the ceramic heater facilitates evaporation of the silver source material, while the steep temperature gradient around the heater enables rapid cooling of the vapor, promoting nanoparticle formation more efficiently than traditional tube furnace systems [16].

Tien and co-workers synthesized silver nanoparticle suspensions in deionized water using an arc discharge technique without adding surfactants. In this approach, highly pure silver wires submerged in deionized water served as electrodes. The process produced metallic silver nanoparticles approximately 10 nm in size along with small concentrations of ionic silver species. Similarly, Siegel and colleagues demonstrated the preparation of AgNPs by sputtering metallic silver directly into glycerol. This method provided an alternative to conventional wet chemical synthesis and generated spherical nanoparticles with an average diameter of nearly 3.5 nm. The dispersion stability remained unchanged even after dilution in aqueous glycerol systems [17].

Chemical Methods

1. Chemical Reduction Method

Chemical reduction is one of the most commonly used methods for synthesizing silver nanoparticles. In this technique, silver ions (Ag^+) are reduced to metallic silver (Ag^0) using reducing agents such as sodium citrate, sodium borohydride, ascorbic acid, Tollens reagent, polyols, hydrogen, dimethylformamide, and polyethylene glycol-based copolymers. Following reduction, the metallic atoms aggregate to form small clusters, which subsequently grow into colloidal nanoparticles [18].

To prevent aggregation and maintain nanoparticle stability, protective or capping agents are generally employed. Surfactants containing functional groups such as thiols, amines, alcohols, and carboxylic acids adsorb onto the nanoparticle surface and inhibit agglomeration or sedimentation while preserving surface characteristics [19].

Silver nanoparticles can also be synthesized at room temperature using polyoxometalates, which act simultaneously as reducing and stabilizing agents. These compounds are water-soluble and capable of multiple electron transfer reactions without structural degradation. Studies have shown that illumination of polyoxometalate-containing silver solutions can effectively generate stable AgNPs. Additionally, environmentally friendly one-step synthesis approaches utilizing mixed-valence molybdenum polyoxometalates have been reported for nanoparticle preparation in aqueous media [20].

2. Microemulsion Technique

The microemulsion method enables the synthesis of silver nanoparticles with controlled size and uniform morphology. In this approach, nanoparticle formation occurs in biphasic aqueous–organic systems where the metal precursor and reducing agent are initially separated into immiscible phases. Reactions occur at the liquid–liquid interface, and the transport of reactants between phases determines nanoparticle formation kinetics [21].

Stabilizer molecules present in the system coat the particle surface and help transfer nanoparticles into the organic phase while preventing aggregation. Despite these advantages, the method has limitations because it frequently requires large quantities of organic solvents and surfactants, which must later be removed from the final product [22].

Certain studies have attempted to reduce toxicity by employing less harmful solvents such as dodecane. Nanoparticles synthesized in nonaqueous media are especially useful in conductive inks and catalytic applications because they remain well dispersed in low vapor pressure organic solvents and exhibit minimal aggregation.

3. UV-Initiated Photoreduction

UV-assisted photoreduction is considered a simple and efficient technique for producing silver nanoparticles. In this method, ultraviolet irradiation reduces silver ions in the presence of stabilizers such as citrate, collagen, polyvinylpyrrolidone, and poly(acrylic acid) [23].

For example, silver nitrate reduced within laponite clay suspensions under UV exposure produced nanoparticles whose size depended on irradiation time. Extended irradiation initially generated larger particles with bimodal distribution, while continued exposure fragmented them into smaller and more uniformly distributed nanoparticles [24].

Different nanoparticle morphologies, including nanospheres, nanowires, and dendritic structures, have also been synthesized at room temperature using UV irradiation in the presence of polyvinyl alcohol. The concentrations of both stabilizer and silver precursor significantly influenced nanoparticle growth and morphology [25].

4. Photoinduced Reduction

Photoinduced and photocatalytic reduction methods are widely employed for silver nanoparticle synthesis because they are clean, versatile, and capable of high spatial control. These methods allow nanoparticle formation in a variety of environments such as polymer matrices, emulsions, surfactant micelles, glasses, and biological systems [26].

Silver nanoparticles with average sizes around 8 nm have been synthesized using photoinduced reduction within polyelectrolyte capsules acting as microreactors. Furthermore, photochemical approaches have been utilized to transform spherical silver nanoparticles into triangular nanoprisms with tunable edge lengths. Stabilizing agents such as citrate and poly(styrene sulfonate) help regulate particle growth during dual-beam illumination processes [27].

Direct photoreduction of silver nitrate in the presence of sodium citrate has also been performed under different light sources, including ultraviolet, blue, green, cyan, orange, and white light.

5. Electrochemical Synthesis

Electrochemical methods provide an effective route for preparing silver nanoparticles with controlled size and improved homogeneity. By altering electrolysis conditions and electrolyte composition, particle characteristics can be tuned precisely [28].

Researchers have synthesized polyphenylpyrrole-coated silver nanospheroids through electrochemical reduction at liquid–liquid interfaces. In another study, monodispersed nanoparticles ranging from 1 to 18 nm were generated within zeolite-modified electrodes. Electrochemical synthesis in aqueous systems has also yielded spherical silver nanoparticles with narrow size distributions using polyvinylpyrrolidone as a stabilizing agent [29].

6. Microwave-Assisted Synthesis

Microwave-assisted synthesis has emerged as a rapid and efficient method for AgNP production. In one approach, silver nanoparticles were synthesized using sodium carboxymethyl cellulose as both reducing and stabilizing agent. The particle size depended on the concentrations of silver nitrate and the polymeric stabilizer. The resulting nanoparticles exhibited excellent uniformity and remained stable for extended periods at room temperature.

Microwave irradiation combined with ethylene glycol has also been used to synthesize silver powders at temperatures between 100°C and 200°C. When polyvinylpyrrolidone was included, nanoparticles ranging from 62 to 78 nm were obtained. Microwave heating has further enabled the synthesis of Fe–Ag bimetallic nanoparticles using oil-soluble silver salts [30].

Different microwave conditions influence nanoparticle surface charge as well. Longer heating durations generally produce negatively charged colloids, whereas shorter heating periods favor positively charged particles.

7. Polymers and Polysaccharides

Natural polysaccharides and synthetic polymers are frequently used for green synthesis and stabilization of silver nanoparticles. Sulfated polysaccharides isolated from marine red algae have been utilized to synthesize stable AgNPs approximately 13 nm in diameter. The sulfate groups participate in reducing silver ions, while the negatively charged polysaccharide layer stabilizes the nanoparticles electrostatically. These nanoparticles remain stable across a broad pH range and under moderate electrolyte concentrations [31].

Ion-exchange polymers containing phosphonic acid groups have also been employed as stabilizing matrices for silver nanoparticles, resulting in cubic and rectangular structures. In addition, copolymers such as cyclodextrin grafted with poly(acrylic acid) can reduce and stabilize silver ions during nanoparticle synthesis. Factors including alkali concentration, heating conditions, and silver precursor concentration strongly affect nanoparticle size and morphology [32].

8. Tollens Method

The Tollens method is a simple and environmentally friendly approach for producing silver nanoparticles with controlled morphology. In this technique, the Tollens reagent, $Ag(NH_3)_2^+$, is reduced by aldehydes or saccharides in the presence of ammonia.

Modified Tollens procedures have been successfully applied for generating silver nanoparticle films, hydrosols, and particles of diverse shapes and sizes. Parameters such as ammonia concentration and the nature of the reducing agent significantly influence nanoparticle morphology and size distribution. Studies have shown that lower ammonia concentrations generally favor the formation of smaller nanoparticles [33].

CONCLUSION

Silver nanoparticles have become an important area of research in nanotechnology because of their remarkable physicochemical, optical, electrical, and biological properties. Their broad-spectrum antimicrobial activity, ability to interact with cellular systems, and potential use in drug delivery, cancer therapy, wound healing, and biosensing have significantly expanded their biomedical relevance. Different synthesis approaches, including physical, chemical, and biological methods, have been successfully employed for the production of AgNPs. However, conventional physical and chemical methods are often associated with limitations such as high energy consumption, use of hazardous chemicals, environmental concerns, and poor biocompatibility. In contrast, green synthesis methods using plants, microorganisms, polymers, and polysaccharides have emerged as sustainable and environmentally friendly alternatives. These methods offer advantages including lower toxicity, cost-effectiveness, enhanced stability, and improved biological compatibility. Furthermore, advancements in characterization techniques have enabled better understanding of nanoparticle morphology, size distribution, surface charge, and functional properties, which are critical for biomedical applications. Despite their enormous therapeutic potential, concerns regarding nanoparticle toxicity, biodistribution, and long-term environmental impact still require careful investigation. Future research should focus on developing standardized green synthesis protocols, improving targeted delivery systems, and conducting extensive clinical and toxicological studies to ensure the safe and effective application of silver nanoparticles in healthcare and other industrial sectors.

References

1. Eker, F., Duman, H., Akdaşçi, E., Bolat, E., Sarıtaş, S., Karav, S., & Witkowska, A. M. (2024). A comprehensive review of nanoparticles: From classification to application and toxicity. *Molecules, 29*, 3482.
2. Bamal, D., Singh, A., Chaudhary, G., Kumar, M., Singh, M., Rani, N., Mundlia, P., & Sehrawat, A. R. (2021). Silver nanoparticles biosynthesis, characterization, antimicrobial activities, applications, cytotoxicity and safety issues: An updated review. *Nanomaterials, 11*, 2086.

3. Wang, L., Hu, C., & Shao, L. (2017). The antimicrobial activity of nanoparticles: Present situation and prospects for the future. *International Journal of Nanomedicine, 12*, 1227–1249. https://doi.org/10.2147/IJN.S121956
4. Paladini, F., & Pollini, M. (2019). Antimicrobial silver nanoparticles for wound healing application: Progress and future trends. *Materials, 12*, 2540.
5. Terra, A. L. M., Kosinski, R. D. C., Moreira, J. B., Costa, J. A. V., & Morais, M. G. D. (2019). Microalgae biosynthesis of silver nanoparticles for application in the control of agricultural pathogens. *Journal of Environmental Science and Health, Part B, 54*, 709–716.
6. Bapat, R. A., Chaubal, T. V., Joshi, C. P., Bapat, P. R., Choudhury, H., Pandey, M., Gorain, B., & Kesharwani, P. (2018). An overview of application of silver nanoparticles for biomaterials in dentistry. *Materials Science and Engineering C, 91*, 881–898.
7. Haque, S., Norbert, C. C., Acharyya, R., Mukherjee, S., Kathirvel, M., & Patra, C. R. (2021). Biosynthesized silver nanoparticles for cancer therapy and in vivo bioimaging. *Cancers, 13*, 6114.
8. Chen, D., Qiao, X., Qiu, X., & Chen, J. (2009). Synthesis and electrical properties of uniform silver nanoparticles for electronic applications. *Journal of Materials Science, 44*, 1076–1081.
9. Kalidasan, B., Pandey, A. K., Saidur, R., & Tyagi, V. V. (2023). Energizing organic phase change materials using silver nanoparticles for thermal energy storage. *Journal of Energy Storage, 58*, 106361.
10. Farooq, S., Dias Nunes, F., & de Araujo, R. E. (2018). Optical properties of silver nanoplates and perspectives for biomedical applications. *Photonics and Nanostructures – Fundamentals and Applications, 31*, 160–167.
11. Ravindran, A., Chandran, P., & Khan, S. S. (2013). Biofunctionalized silver nanoparticles: Advances and prospects. *Colloids and Surfaces B: Biointerfaces, 105*, 342–352.
12. Hoang, V. T., Mai, M., Thi Tam, L., Vu, N. P., Tien Khi, N., Dinh Tam, P., Quang Huy, T., Le, A. T., Xuan Dinh, N., & Tran, V. H. (2020). Functionalized-AgNPs for long-term stability and its applicability in the detection of manganese ions. *Advanced Polymer Technology, 2020*, 9437108.
13. Dhaka, A., Chand Mali, S., Sharma, S., & Trivedi, R. (2023). A review on biological synthesis of silver nanoparticles and their potential applications. *Results in Chemistry, 6*, 101108.
14. Mustafa, G., Hasan, M., Yamaguchi, H., Hitachi, K., Tsuchida, K., & Komatsu, S. (2020). A comparative proteomic analysis of engineered and biosynthesized silver nanoparticles on soybean seedlings. *Journal of Proteomics, 224*, 103833.

15. Kruis, F., Fissan, H., & Rellinghaus, B. (2000). Sintering and evaporation characteristics of gas-phase synthesis of size-selected PbS nanoparticles. *Materials Science and Engineering: B, 69*, 329–334.
16. Magnusson, M., Deppert, K., Malm, J., Bovin, J., & Samuelson, L. (1999). Gold nanoparticles: Production, reshaping, and thermal charging. *Journal of Nanoparticle Research, 1*, 243–251.
17. Jung, J., Oh, H., Noh, H., Ji, J., & Kim, S. (2006). Metal nanoparticle generation using a small ceramic heater with a local heating area. *Journal of Aerosol Science, 37*, 1662–1670.
18. Wiley, B., Sun, Y., Mayers, B., & Xi, Y. (2005). Shape-controlled synthesis of metal nanostructures: The case of silver. *Chemistry – A European Journal, 11*, 454–463.
19. Evanoff, D. D., Jr., & Chumanov, G. (2004). Size-controlled synthesis of nanoparticles. 2. Measurement of extinction, scattering, and absorption cross sections. *The Journal of Physical Chemistry B, 108*, 13957–13962.
20. Merga, G., Wilson, R., Lynn, G., Milosavljevic, B., & Meisel, D. (2007). Redox catalysis on "naked" silver nanoparticles. *The Journal of Physical Chemistry C, 111*, 12220–12226.
21. Oliveira, M. M., Ugarte, D., Zanchet, D., & Zarbin, A. J. G. (2005). Influence of synthetic parameters on the size, structure, and stability of dodecanethiol-stabilized silver nanoparticles. *Journal of Colloid and Interface Science, 292*, 429–435.
22. Troupis, A., Hiskia, A., & Papaconstantinou, E. (2002). Synthesis of metal nanoparticles by using polyoxometalates as photocatalysts and stabilizers. *Angewandte Chemie International Edition, 41*, 1911–1914.
23. Zhang, G., Keita, B., Dolbecq, A., Mialane, P., Sécheresse, F., Miserque, F., et al. (2007). Green chemistry-type one-step synthesis of silver nanostructures based on MoV–MoVI mixed-valence polyoxometalates. *Chemistry of Materials, 19*, 5821–5823.
24. Krutyakov, Y., Olenin, A., Kudrinskii, A., Dzhurik, P., & Lisichkin, G. (2008). Aggregative stability and polydispersity of silver nanoparticles prepared using two-phase aqueous organic systems. *Nanotechnologies in Russia, 3*, 303–310.
25. Zhang, W., Qiao, X., & Chen, J. (2007). Synthesis of nanosilver colloidal particles in water/oil microemulsion. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 299*, 22–28.
26. Cozzoli, P. D., Comparelli, R., Fanizza, E., Curri, M. L., Agostiano, A., & Laub, D. (2004). Photocatalytic synthesis of silver nanoparticles stabilized by TiO2 nanorods: A semiconductor/metal nanocomposite in homogeneous nonpolar solution. *Journal of the American Chemical Society, 126*, 3868–3879.

27. Huang, H., & Yang, Y. (2008). Preparation of silver nanoparticles in inorganic clay suspensions. *Composites Science and Technology, 68*, 2948–2953.
28. Zhou, Y., Yu, S. H., Wang, C. Y., Li, X. G., Zhu, Y. R., & Chen, Z. Y. (1999). A novel ultraviolet irradiation photoreduction technique for the preparation of single-crystal Ag nanorods and Ag dendrites. *Advanced Materials, 11*, 850–852.
29. Shchukin, D. G., Radtchenko, I. L., & Sukhorukov, G. B. (2003). Photoinduced reduction of silver inside microscale polyelectrolyte capsules. *ChemPhysChem, 4*, 1101–1103.
30. Jin, R., Cao, Y. C., Hao, E., Métraux, G. S., Schatz, G. C., & Mirkin, C. A. (2003). Controlling anisotropic nanoparticle growth through plasmon excitation. *Nature, 425*, 487–490.
31. Johans, C., Clohessy, J., Fantini, S., Kontturi, K., & Cunnane, V. J. (2002). Electrosynthesis of polyphenylpyrrole coated silver particles at a liquid–liquid interface. *Electrochemistry Communications, 4*, 227–230.
32. Zhang, Y., Chen, F., Zhuang, J., Tang, Y., Wang, D., Wang, Y., et al. (2002). Synthesis of silver nanoparticles via electrochemical reduction on compact zeolite film modified electrodes. *Chemical Communications, 24*, 2814–2815.
33. Ma, H., Yin, B., Wang, S., Jiao, Y., Pan, W., Huang, S., et al. (2004). Synthesis of silver and gold nanoparticles by a novel electrochemical method. *ChemPhysChem, 24*, 68–75.

***Corresponding Author:** Dr. Azharuddin, [1]Department of Pharmaceutics, Lords University, Alwar, Rajasthan, India