

The effect investigation of various parameters on the growth of silver nanoparticles via atmospheric pressure plasma

Zohreh Dehghani*, Elnaz Khalilzadeh

Plasma and Fusion Research School, Nuclear Science and Technology Research Institute, Tehran, Iran.

*Corresponding author: dehghanyz93@gmail.com

Original Research

Abstract:

Received:
24 August 2023
Revised:
2 November 2023
Accepted:
13 November 2023
Published online:
10 January 2024

In this work atmospheric pressure plasma has been used for the synthesis of silver (Ag) nanoparticles immersed in liquid. We study the effects of various parameters such as the electrolyte, the process time, and the applied electric current on the synthesis of Ag nanoparticles. The products are analyzed by transmission electron microscopy (TEM), X-ray diffraction (XRD) and UV-Vis spectroscopy. The results obtained show that the parameters mentioned have a major influence on the size and number of nanoparticles produced. In this study, the absorption peak of the Ag nanoparticles is at a wavelength of 420 nm. Moreover, the size of the particles is found between 10 – 20 nm. It is worth mentioning that there is an inverse relationship between the ethylene glycol concentration and the nanoparticle size. As the ethylene glycol concentration in the electrolyte increases, the nanoparticle size decreases. It is also expected that the morphology and size of the nanoparticles will become more uniform as the reaction time increases.

Keywords: Ag nanoparticles; Atmospheric pressure plasma; Nanoparticle morphology; TEM, UV-Vis spectroscopy

1. Introduction

In recent years, nanomaterials, especially metal nanoparticles, have attracted much significant attention in the field of science and technology [1–8]. Recently, silver (Ag) nanoparticles have attracted great interest, mainly because of their new technological applications in various fields such as optics [9–11], sensing [12–14], catalysis surface-enhanced Raman scattering [15], biology [16, 17] and antimicrobial agents [18–20].

There are several common methods for the preparation of Ag nanoparticles, and the methods of chemical and physical synthesis are very common and obvious. It is worth noting that despite their many advantages, they also have some disadvantages in terms of the synthesis process and nanoparticle properties such as size, size distribution, cost and scalability. For instance, chemically synthesized nanoparticles are expensive, toxic and energy consuming, and therefore not suitable for biological applications [21–23]. Moreover, this method is laborious to control the size and shape of nanoparticles, which determine the physical, catalytic, an-

tibacterial and other properties. Regarding physical methods, temperature adjustments, instrumentation, and vacuum conditions are needed for nanoparticle synthesis.

The synthesis of Ag nanoparticles has already been carried out using various methods such as laser ablation [24, 25], gamma irradiation [26, 27], electron irradiation [28, 29], chemical reduction [30, 31], photochemical methods [32], microwave methods [33], biological synthesis methods [34, 35] and electrochemical methods [36]. Among these methods, the electrochemical method is a simple technique to synthesize Ag nanoparticles, which makes it possible to obtain particles with high purity using fast and simple procedures and to easily control the particle size by adjusting the current density. However, despite the cheapness and apparent simplicity of the method, it is very difficult to synthesize nanoparticles electrochemically without stabilizer. In the typical traditional electrochemical method, the reactions are caused by solid electrodes into an electrolyte containing the ionic liquids. In the plasma- electrochemical method, the gas discharge is coupled simultaneously with the solution to induce reactions in the presence of a solid

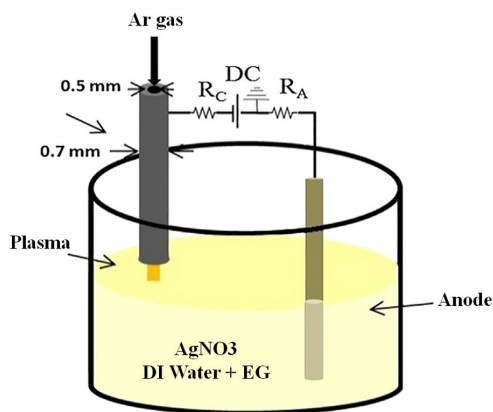


Figure 1. The schematic of Ag nanoparticles synthesis device.

electrode in the electrolytes. Recently, many studies on this method have indicated that it can accelerate the electron transfer rate and increase the synthesis rate of nanoparticles accordingly [37–39].

The synthesis of nanoparticles using plasma-liquid interfaces has a particular advantage over the traditional electrochemical method due to the reducing agent. This is because a non-thermal atmospheric pressure plasma is generated above the electrolyte, avoiding the difficulties of isolating nanoparticle production. In addition, toxic stabilizers and reducing agents are not required in this method, and the synthesis of nanoparticles occurs continuously during plasma irradiation. Although there are many papers on the production of nanoparticles with this method, many important questions remain unanswered regarding the effects of different plasma parameters on nanoparticle growth. In this work, therefore, an Ar atmospheric pressure plasma was first used for the synthesis of Ag nanoparticles immersed in a liquid. Subsequently the influence of various parameters such as the electrolyte, the process time, and the electric current applied to the electrodes has experimentally been investigated.

2. Material and methods

2.1 Plasma reactor

For the synthesis of Ag particles, a schematic experimental setup is used, which is shown in Fig. 1. A DC atmospheric pressure plasma system on the surface of the liquid is created by a capillary tube (cathode: made of stainless steel with inner diameter: 0.5 mm; outer diameter: 0.7 mm; length: 7 cm). It is located at 3 to 5 mm above the surface of the solution and 4 cm from the anode (made of Pt with 1 cm², 0.001 in thick). The high voltage applied to the tube is the 2.1 kV and plasma is kept stable (a ballast resistor). Both the current and the voltage are measured with a high voltage probe (Tektronix P6015A). The Ar gas flow is coupled to the system and is kept constant at 180 sccm. In addition, the irradiation times are 10, 20 and 30 minutes.

2.2 Material

The reaction medium (inner diameter: 8 cm; length: 3 cm) contains a solution of deionized (DI) water: ethylene glycol



Figure 2. Ag nanoparticles solution in water after irradiation for 20 min.

with different percentages and silver nitrate (AgNO₃) at room temperature. For the synthesis of silver nanoparticles (Ag NPs), AgNO₃ is purchased from Merck.

2.3 Material characteristic

The morphology of the Ag NPs was analyzed by TEM (TEM: Zeiss-EM10C-80 KV). The UV-Vis absorption (ultraviolet-visible light) was measured using a (UV-Vis-NIR) spectrophotometer (Spectrophotometer: PG Instruments model T80+). In addition, the XRD pattern was recorded using an X'Pert MPD (Philips) X-ray diffraction meter with Co-K_α radiation (1.79 Å).

3. Results and discussion

The image of Ag nanoparticles in DI water is shown in Fig. 2. Due to the synthesis of Ag nanoparticles by plasma, the color of the samples changed from colorless to brown, which was consistent with the sources and indicated the preparation of a colloidal suspension of silver nanoparticles. The silver nanoparticles were stable in the solution for months and no precipitation was observed. Various analytical methods were used to verify the properties of the nanoparticles. To confirm the presence of nanoparticles, the absorption spectrum of the sample was first examined. It is worth noting that one of the most interesting features of metal nanoparticles is the surface plasmon resonance, which represents their unique optical properties. The surface plasmon resonance depends on several factors, such as the size and shape of the nanoparticles the distance between them and the refractive index of the surrounding environment, etc. Therefore, the presence of a peak in this range, which can be detected with an ultraviolet spectrometer, therefore indicates the existence of the silver nanoparticles. Hence, UV-Vis spectroscopy can be a simple and reliable method to analyze the stability of solutions containing nanoparticles. Studies have shown that the nanoparticle size is an

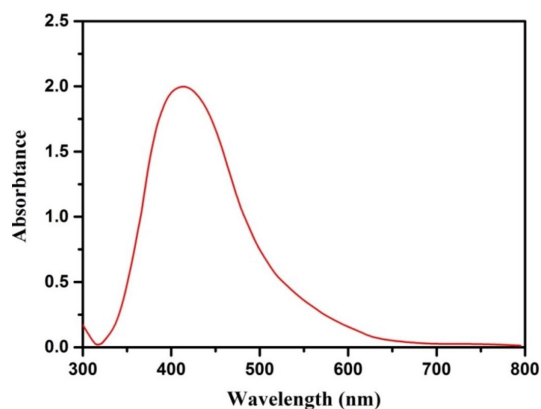


Figure 3. UV-Vis absorption spectra for Ag nanoparticle in DI water during irradiation time 20 min in current 5 mA.

important factor for the red shift of the peak wavelength and the change in its intensity and the observed colors of the solution.

Fig. 3 indicated the absorption spectra of the Ag nanoparticles synthesized in DI water at an irradiation time of 20 minutes and a current of 5 mA. As you can see, the surface plasmon is formed at a wavelength of 415 nm, which is associated with the silver nanoparticles. Ag nanoparticles have a surface plasmon resonance in the range of 400 to 450 nm, depending on their size and shape. Beyond this, there is no further visible maximum, so it can be assumed that the nanoparticles are spherical or quasi-spherical.

The Ag nanoparticles are clearly visible in the TEM image shown in Fig. 4. As can be seen from the TEM image, the Ag nanoparticles are mainly spherical with a diameter of 10–20 nm and in some areas, they are accumulated or scattered. From the size distribution of the produced silver nanoparticles, the average size of the particles in the sample with Image j software is about 8 nm.

X-ray diffraction (XRD) of Ag nanoparticles is shown in Fig. 5. It is worth mentioning that XRD was used to determine the structure and chemical composition of the prepared nanoparticles. As can be seen in the figure, there are clear peaks at the angles of $2\theta=38.17^\circ$, 44.31° , 64.5° and 77.05° . due to the (1 1 1), (2 2 0), (2 0 0) and (3 1 1) planes of silver

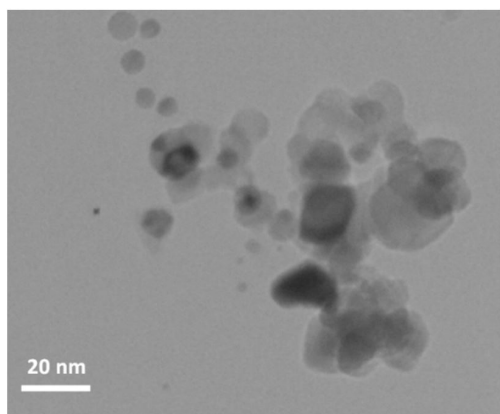


Figure 4. TEM image of nanoparticle after 20 min irradiation.

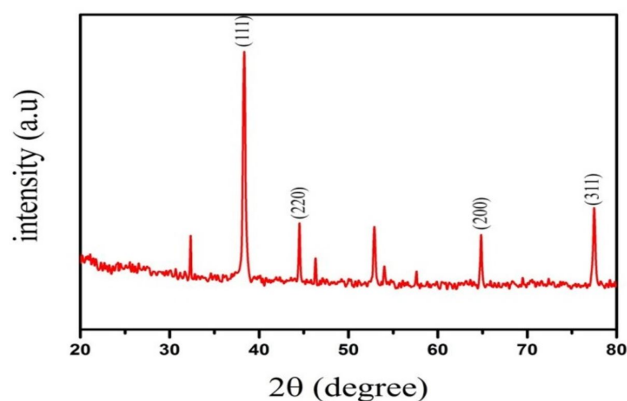


Figure 5. XRD patterns of Ag nanoparticles after 20 min plasma irradiation.

FCC structure respectively.

In the continuation of this section, the effect of different parameters on the shape and size of the nanoparticles is investigated in three steps: (1) the effect of the type of electrolyte used in the production of silver nanoparticles, (2) the effect of the reaction time and (3) the current used to produce these nanoparticles.

3.1 The effect of electrolyte (reducing agent) on particle size and morphology

Ag nanoparticles were prepared using different concentrations of ethylene glycol with a constant concentration of silver nitrate in neutral media. 0.2 mM separately prepared silver nitrate is dissolved in 20 mL of a solution containing water and ethylene glycol in different volume ratios (DI water: ethylene glycol (100:0, 75:25, 50:50)). Fig. 6 shows the UV-Vis spectra of Ag nanoparticles using atmospheric pressure plasma in different electrolyte concentrations after 20 minutes of irradiation at a current of 5 mA. As you seen, the position of the peak wavelength changes and shifts to shorter wavelengths (i.e. from 415 nm to 390 nm) with increasing concentration of EG in the solution. This response is fully consistent with May's classical theorem i.e. absorp-

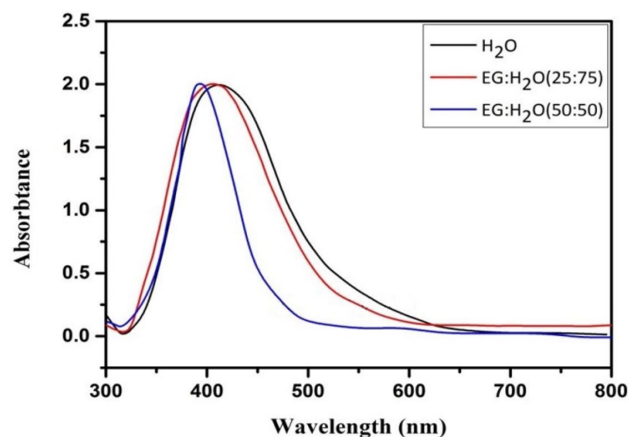


Figure 6. The UV-Vis light absorption spectra for Ag nanoparticles 20 min plasma irradiation with different volume ratios DI water and EG.

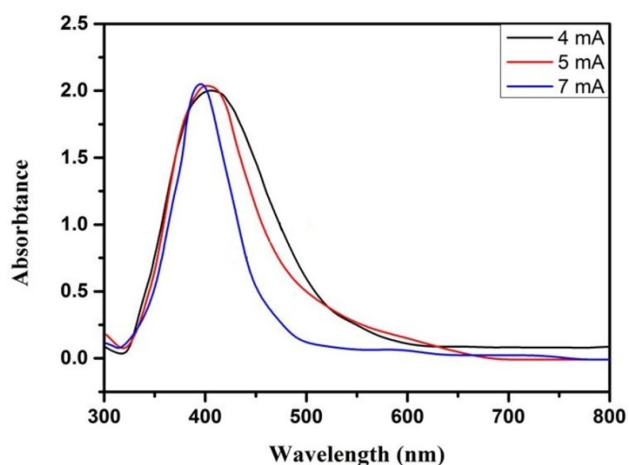


Figure 7. The UV–Vis light absorption spectra Ag nanoparticles for different current and 20 min plasma irradiation.

tion spectra of smaller particles indicate blue shifted than of larger particle. As a result, to increase the concentration of EG in the solution, the particle sizes decreases. Furthermore, the peak intensity also does not change significantly with the variation of the volume percentage of electrolyte contents (water and EG) and just the absorption peaks become narrower. It indicates that there was no change in the amount of Ag nanoparticles in the solution.

One of the parameters determining the nanoparticle size is concentration and type of electrolyte. Note that different reducing agents could be varying power to decrease materials. Hence according to its reducing power, nanoparticles with various sizes and morphologies can be produced. It has been claimed that a stronger reducer, under the same condition of other parameters, is capable of producing finer particles compared to a weak reducer. On the other hand, there is an inverse relationship between the reducing agent concentration and the nanoparticle size. When reducing agent concentration increases in electrolyte the nanoparticle size decreases. Moreover, the nanoparticle size distribution and shape are less sensitive to change of the reducing agent concentration compared with other influencing factors.

3.2 The effect of reaction time and current density on the size of silver nanoparticles

Fig. 7 indicates the UV–Vis spectra of Ag nanoparticles synthesized with atmospheric pressure plasma for different currents (4, 5 and 7 mA) after 20 minutes of plasma irradiation. The Ag nanoparticles were synthesized in 20 ml of a solution containing separately prepared DI water, ethylene glycol (DI water: ethylene glycol (75:25)) and 0.2 mM AgNO_3 . As seen, the intensity of absorption peaks of the Ag nanoparticles slowly increases as you increase the current density from 4–7 mA. In addition to the increase in current density, the spectrum peak shifts to shorter wavelengths and the spectrum becomes narrower.

One of the important parameters that determine particle size and distribution is the reaction time. Fig. 8 shows the absorption spectrum of Ag nanoparticles produced under the conditions mentioned in Fig. 8 with a current of 5 mA at different plasma irradiation times (10, 20 and 30 minutes).

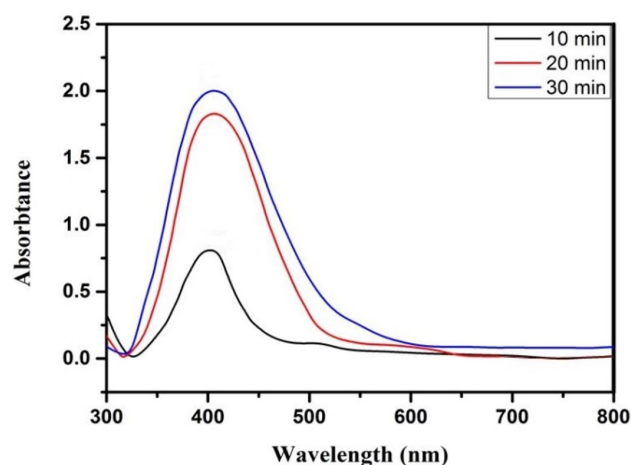


Figure 8. The UV–Vis light absorption spectra for Ag nanoparticle under different irradiation with current 5 mA.

As the irradiation time increases, the spectra show higher absorbance values and larger peak area, indicating higher production efficiency. Moreover, the position of the peaks for all times is between 490 and 410 nm which indicates the average size of the nanoparticles.

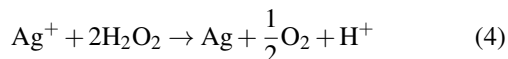
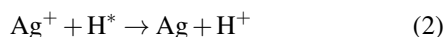
When the precursor is added to the reaction solution, nucleation begins immediately and tiny nanocrystals form, causing a marked change in the color of the solution. Over time, the nuclei formed tend to aggregate and form larger particles. Also, the more silver ions are reduced in the metallic form, as more time passes from the reaction. At some point, all the silver is reduced to silver particles, and from then on only the size of the particles changes. Therefore, to achieve the reaction time, it is necessary to choose an optimal state between reaction efficiency and particle size. In addition, the morphology and size of the particles are expected to become more uniform as the reaction time increases.

4. Mechanism

When the Ar plasma comes into contact with the electrolyte, plasma species such as ions, radicals and energetic electrons are transferred to the electrolyte-plasma interface, causing the reduction of Ag ions (equation 2). In electrolyte-plasma electrochemistry, the dominant reactions are thermal-electron-collision reactions. A few minutes after the start of the process, the color of the solution near the electrolyte-plasma interface has changed, indicating the growth of nanoparticles. Due to Brownian motion, the nanoparticles spread over more and more space in the solution volume over time, so that the color of the solution gradually changed from colorless to brown. However, as the amount of AgNO_3 increases, more nanoparticles are also produced. This result is quite logical, as the Ag ions are reduced by the electrons and eventually turn into Ag nanoparticles.

In addition, species such as oxygen, OH and hydrogen radicals are produced during the plasma discharge in the electrolyte due to the water decomposition. The advantage of this process is the production of non-toxic reducing

agents in the electrolyte. The reduction equations for these processes are as follows:



To utilize plasma according to equation 1, water molecules are decomposed to radicals such as H^* and OH^* . Then, in some cases, the ions are lessened by hydrogen radicals (equation 2). In addition, equation 4 shows the reduction reaction of Ag^+ ions by H_2O_2 . In many reports of nanoparticles prepared without the presence of a stabilizing agent, they are highly dispersed in the environment due to electrostatic repulsion and the mechanism is not yet fully understood. One of the existing assumptions is that the effect of the hydroxyl groups in the environment and their absorption on the surface of nanoparticles. The metal ions are reduced by hydroxyl groups as reducing agents. It is worth mentioning that the plasma improves the dispersion behavior of nanoparticles by accelerating the formation of these groups. In other words, the hydroxyl groups are absorbed on the surfaces of the nanoparticles and enhance the electrostatic repulsion on these surfaces. Consequently, this can reduce the accumulation of particles.

5. Conclusion

This article deals with the synthesis of Ag nanoparticles using atmospheric pressure microplasma. We have investigated their physical, chemical, and optical properties using XRD, TEM and UV-Vis spectroscopy. The TEM image and XRD patterns confirm the formation of Ag nanoparticles in an electrolyte consisting of ethylene glycol as solvent and DI water. Valuable conclusions were drawn from the results of this study. The nanoparticles produced using this strategy initially had a uniform particle size and a quasi-spherical shape. In addition, the morphology and size of the particles varied with the change in plasma parameters and irradiation time.

Ethical approval

This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Author contribution statement

Zohreh Dehghani did the experimental work. Elnaz Khalilzadeh did analysis of data. Both authors wrote the paper.

Data Availability Statement

All data generated or analyzed during the reported research are presented in the article.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the OICCPress publisher. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0>.

References

- [1] T. K. Sau and A. L. Rogach. "Nonspherical noble metal nanoparticles: colloid-chemical synthesis and morphology control". *Adv. Mater.*, **22**:1781–804, 2010. DOI: <https://doi.org/10.1002/adma.200901271>.
- [2] P. R. Sajanlal, T. S. Sreeprasad, A. K. Samal, and T. Pradeep. "Anisotropic nanomaterials: structure, growth, assembly, and functions". *Nano Rev.*, **2**:5883, 2011. DOI: <https://doi.org/10.3402/nano.v2i0.5883>.
- [3] M. Rycenga, C. M. Cobley, J. Zeng, W. Li, C. H. Moran, Q. Zhang, D. Qin, and Y. Xia. "Controlling the synthesis and assembly of silver nanostructures for plasmonic applications". *Chem. Rev.*, **111**:3669–712, 2011. DOI: <https://doi.org/10.1021/cr100275d>.
- [4] D.J. Anderson and M. A. Moskovits. "SERS-active system based on silver nanoparticles tethered to a deposited silver film". *J. Phys. Chem. B.*, **110**:13722–7, 2006. DOI: <https://doi.org/10.1021/jp055243y>.
- [5] H. Cong, C. F. Becker, S. J. Elliott, M. W. Grinstaff, and Jr. J. A. Porco. "Silver nanoparticle-catalyzed Diels-Alder cycloadditions of 2'-hydroxychalcones". *J. Am. Chem. Soc.*, **132**:7514–8, 2010. DOI: <https://doi.org/10.1021/ja102482b>.
- [6] S. E. Skrabalak, L. Au, X. Li, and Y. Xia. "Facile synthesis of Ag nanocubes and Au nanocages". *Nat. Protoc.*, **2**:2182–90, 2007. DOI: <https://doi.org/10.1038/nprot.2007.326>.
- [7] J. Fang, H. You, P. Kong, Y. Yi, X. Song, and B. Ding. "Dendritic silver nanostructure growth and evolution in

- replacement reaction". *Cryst. Growth Des.*, **30**:864–7, 2007. DOI: <https://doi.org/10.1021/cg0604879>.
- [8] J. An, B. Tang, X. Ning, J. Zhou, S. Xu, B. Zhao, W. Xu, C. Corredor, and J. R. Lombardi. "Photoinduced shape evolution: from triangular to hexagonal silver nanoplates". *J. Phys. Chem. C.*, **111**:18055–9, 2007. DOI: <https://doi.org/10.1021/jp0745081>.
- [9] L. Gharibshahi, E. Saion, E. Gharibshahi, A. H. Shaari, and K. A. Matori. "Structural and optical properties of Ag nanoparticles synthesized by thermal treatment method". *Materials*, **10**:402, 2017. DOI: <https://doi.org/10.3390/ma10040402>.
- [10] S. M. Hosseini, I. A. Sarsari, P. Kameli, and H. Salamat. "Effect of Ag doping on structural, optical, and photocatalytic properties of ZnO nanoparticles". *J. Alloys Compd.*, **640**:408–15, 2015. DOI: <https://doi.org/10.1016/j.jallcom.2015.03.136>.
- [11] Y. X. Zhang and Y. H. Wang. "Nonlinear optical properties of metal nanoparticles: a review". *RSC Adv.*, **7**:45129–44, 2017. DOI: <https://doi.org/10.1039/C7RA07551K>.
- [12] Q. Wang, S. L. Dong, D. D. Tao, Z. Li, and Y. B. Jiang. "Ag (I)-thiolate coordination polymers: Synthesis, structures and applications as emerging sensory ensembles". *Coord. Chem. Rev.*, **432**:213717, 2021. DOI: <https://doi.org/10.1016/j.ccr.2020.213717>.
- [13] O. J. Osborne, K. Mukaigasa, H. Nakajima, B. Stolpe, I. Romer, U. Philips, I. Lynch, S. Mourabit, S. Hirose, J. R. Lead, and M. Kobayashi. "Sensory systems and ionocytes are targets for silver nanoparticle effects in fish". *Nanotoxicology*, **10**:1276–86, 2016. DOI: <https://doi.org/10.1080/17435390.2016.1206147>.
- [14] M. Zhu, T. He, and C. Lee. "Technologies toward next generation human machine interfaces: From machine learning enhanced tactile sensing to neuromorphic sensory systems". *Appl. Phys. Rev.*, **7**, 2020. DOI: <https://doi.org/10.1063/5.0016485>.
- [15] K. Zhao, C. Wu, Z. Deng, Y. Guo, and B. Peng. "Preparation of silver decorated silica nanocomposite rods for catalytic and surface-enhanced Raman scattering applications". *RSC Adv.*, **5**:52726–36, 2015. DOI: <https://doi.org/10.1039/C5RA08076B>.
- [16] E. Abbasi, M. Milani, S. Fekri Aval, M. Kouhi, A. Akbarzadeh, H. Tayefi Nasrabadi, P. Nikasa, S. W. Joo, Y. Hanifehpour, K. Nejati-Koshki, and M. Samiei. "Silver nanoparticles: synthesis methods, bio-applications and properties". *Crit. Rev. Microbiol.*, **42**:173–80, 2016. DOI: <https://doi.org/10.3109/1040841X.2014.912200>.
- [17] R. A. Hamouda, M. H. Hussein, R. A. Abo-Elmagd, and S. S. Bawazir. "Synthesis and biological characterization of silver nanoparticles derived from the cyanobacterium *Oscillatoria limnetica*". *Sci. Rep.*, **9**:13071, 2019. DOI: <https://doi.org/10.1038/s41598-019-49444-y>.
- [18] A. S. Hassanien and U. T. Khatoon. "Synthesis and characterization of stable silver nanoparticles, Ag-NPs: Discussion on the applications of Ag-NPs as antimicrobial agents". *Phys. B: Condens. Matter.*, **554**:21–30, 2019. DOI: <https://doi.org/10.1016/j.physb.2018.11.004>.
- [19] B. Buszewski, V. Railean-Plugaru, P. Pomastowski, K. Rafińska, M. Szultka-Mlynska, P. Golinska, M. Wypij, D. Laskowski, and H. Dahm. "Antimicrobial activity of biosilver nanoparticles produced by a novel *Streptacidiphilus durhamensis* strain". *J. Microbiol. Immunol. Infect.*, **51**:45–54, 2018. DOI: <https://doi.org/10.1016/j.jmii.2016.03.002>.
- [20] S. Perumal, R. Atchudan, S. Ramalingam, S. Aldawood, N. Devarajan, W. Lee, and Y. R. Lee. "Silver nanoparticles loaded graphene-poly-vinylpyrrolidone composites as an effective recyclable antimicrobial agent". *Environ. Res.*, **216**:114706, 2023. DOI: <https://doi.org/10.1016/j.envres.2022.114706>.
- [21] J. García-Barrasa, J. M. López de Luzuriaga, and M. Monge. "Silver nanoparticles: synthesis through chemical methods in solution and biomedical applications". *Cent. Eur. J. Chem.*, **9**:7–19, 2011. DOI: <https://doi.org/10.2478/s11532-010-0124-x>.
- [22] A. P. Reverberi, N. T. Kuznetsov, V. P. Meshalkin, M. Salerno, and B. Fabiano. "Systematical analysis of chemical methods in metal nanoparticles synthesis". *Theor. Found. Chem. Eng.*, **50**:59–66, 2016. DOI: <https://doi.org/10.1134/S0040579516010127>.
- [23] S. Panigrahi, S. Kundu, S. Ghosh, S. Nath, and T. Pal. "General method of synthesis for metal nanoparticles". *J. Nanoparticle Res.*, **6**:411–4, 2004. DOI: <https://doi.org/10.1007/s11051-004-6575-2>.
- [24] A. Pyatenko, K. Shimokawa, M. Yamaguchi, O. Nishimura, and M. Suzuki. "Synthesis of silver nanoparticles by laser ablation in pure water". *Appl. Phys. A.*, **79**:803–6, 2004. DOI: <https://doi.org/10.1007/s00339-004-2841-5>.
- [25] M. Rafique, M. S. Rafique, U. Kalsoom, A. Afzal, S. H. Butt, and A. Usman. "Laser ablation synthesis of silver nanoparticles in water and dependence on laser nature". *Opt. Quantum Electron.*, **51**, 2019. DOI: <https://doi.org/10.1007/s11082-019-1902-0>.
- [26] N. Eghbalifam, M. Frounchi, and S. Dadbin. "Antibacterial silver nanoparticles in polyvinyl alcohol/sodium alginate blend produced by gamma irradiation". *Int. J. Biol. Macromol.*, **80**:170–6, 2015. DOI: <https://doi.org/10.1016/j.ijbiomac.2015.06.042>.
- [27] de. Freitas, L. Freitas, G. H. Varca, J. G. dos Santos Batista, and A. Benévolo Lugão. "An overview of the synthesis of gold nanoparticles using radiation

- technologies". *Nanomaterials*, **8**:939, 2018. DOI: <https://doi.org/10.3390/nano8110939>.
- [28] R. A. Roca, P. S. Lemos, J. Andrés, and E. Longo. "Formation of Ag nanoparticles on metastable β -Ag₂WO₄ microcrystals induced by electron irradiation". *Chem. Phys. Lett.*, **644**:68–72, 2016. DOI: <https://doi.org/10.1016/j.cplett.2015.11.048>.
- [29] J. Gong, H. Liu, Y. Jiang, S. Yang, X. Liao, Z. Liu, and S. Ringer. "In-situ synthesis of Ag nanoparticles by electron beam irradiation". *Mater Charact.*, **110**:1–4, 2015. DOI: <https://doi.org/10.1016/j.matchar.2015.09.030>.
- [30] M. Gakiya-Teruya, L. Palomino-Marcelo, and J. C. Rodriguez-Reyes. "Synthesis of highly concentrated suspensions of silver nanoparticles by two versions of the chemical reduction method". *Methods Protoc.*, **2**: 3, 2018. DOI: <https://doi.org/10.3390/mps2010003>.
- [31] R. Vazquez-Muñoz, M. J. Arellano-Jimenez, F. D. Lopez, and J. L. Lopez-Ribot. "Protocol optimization for a fast, simple and economical chemical reduction synthesis of antimicrobial silver nanoparticles in non-specialized facilities". *BMC Res Notes.*, **12**:1–6, 2019. DOI: <https://doi.org/10.1186/s13104-019-4813-z>.
- [32] I. Moglia, M. Santiago, M. Soler, and A. Olivera-Nappa. "Silver nanoparticle synthesis in human ferritin by photochemical reduction". *JIBC*, **206**:111016, 2020. DOI: <https://doi.org/10.1016/j.jinorgbio.2020.111016>.
- [33] A. K. Mandal and R. Sen. "An overview on microwave processing of material: a special emphasis on glass melting". *Mater. Manuf. Process.*, **32**:1–20, 2017. DOI: <https://doi.org/10.1080/10426914.2016.1151046>.
- [34] A. Sharma and S. Kumar. "Synthesis and green synthesis of silver nanoparticles. Polymer nanocomposites based on silver nanoparticles". *Engineering Materials.*, :25–64, 2021. DOI: <https://doi.org/10.1007/978-3-030-44259-0-2>.
- [35] P. B. Khodke, R. R. Popat, P. V. Burakale, P. P. Chinchole, and V. N. Shrikhande. "Silver nanoparticles-A review". *Res J Pharm Technol.*, **10**:1820–33, 2017. DOI: <https://doi.org/10.5958/0974-360X.2017.00321.3>.
- [36] G. R. Nasretdinova, R. R. Fazleeva, R. K. Mukhitova, I. R. Nizameev, M. K. Kadirov, A. Y. Ziganshina, and V. V. Yanilkin. "Electrochemical synthesis of silver nanoparticles in solution". *Electrochem. commun.*, **50**:69–72, 2015. DOI: <https://doi.org/10.1016/j.elecom.2014.11.016>.
- [37] Y. L. Thong, O. H. Chin, B. H. Ong, and N. M. Huang. "Synthesis of silver nanoparticles prepared in aqueous solutions using helium dc microplasma jet". *Jpn. J. Appl. Phys.*, **55**:01AE19, 2015. DOI: <https://doi.org/10.7567/JJAP.55.01AE19>.
- [38] L. Lin and Q. Wang. "Microplasma: a new generation of technology for functional nanomaterial synthesis". *Plasma Chem. Plasma Process.*, **35**:925–62, 2015. DOI: <https://doi.org/10.1007/s11090-015-9640-y>.
- [39] M. T. Saleem, S. Bashir, and M. Bashir. "Microplasma assisted synthesis of silver nanoparticles capped with PVA, PVP and Sucrose". *Nano Ex.*, **2**:020026, 2021. DOI: <https://doi.org/10.1088/2632-959X/ac0965>.