



Morphological and structural properties of silver/chlorargyrite nanoparticles prepared using *Senecio madagascariensis* leaf extract and interaction studies with bovine serum albumin

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Abstract

Senecio madagascariensis leaf extract was used to synthesize silver/chlorargyrite nanoparticles. XRD diffraction patterns confirmed the nanocrystalline phase with a face-centered crystal structure of metallic silver. The TEM revealed that the silver and silver chloride nanoparticles were spherical and polydisperse with a decreasing size with respect to the concentration of the silver salt and an average size in the range 13–25 nm. The optical band gaps for Ag/AgCl are 2.71, 2.73, and 2.66 eV for nanoparticles prepared with 20 mM, 50 mM, and 100 mM, respectively. The SEM–EDX confirmed the presence of elemental Cl and Ag. The results show that *S. madagascariensis* could be used to prepare environmentally friendly bioactive silver nanoparticles. Fluorescence data indicated that static quenching played a role in the formation of the complex between AgNPs and BSA.

Introduction

Silver and silver chloride nanoparticles (Ag/AgCl NPs) have been explored for different biomedical applications such as antimicrobial and photothermal therapy (PTT) [1]. Chemical synthesis of Ag/AgCl NPs poses different challenges some of which could be overcome by using the green synthesis methods that are biocompatible and environmentally friendly [2]. Interest in silver nanoparticles (AgNPs) are due to their potential applications such as in biological assays [3]. They are biologically significant due to their nanometer size, which enables them to interact with vital biomolecules like DNA, proteins, and viruses as well as penetrate cellular membranes [4]. They also have unique optical properties that set them apart from their bulk counterparts.

Challenges posed by the chemical synthesis of silver nanoparticles include agglomeration, stability, environmental concerns, reproducibility, and the ability to control their size

and shape [5, 6]. Biosynthesis of silver nanoparticles using plant extracts [7, 8] and microbes like bacteria [9, 10] and algae [11] are receiving considerable attention. Chandhirasekar et al., reported the successful green synthesis of Ag/AgCl NPs using the Asteraceae family [12]. *Stachys spectabilis* leaves have been used for the synthesis of spherical silver nanoparticles with an average particle size of 10.8 nm [13]. Some species of *Senecio* genus, including *S. vulgaris*, *S. inaequidens*, *S. stebianus*, and *S. tenuifolius*, have been shown to have anti-proliferative effects in cancer-derived cells more recently [14]. To the best of our knowledge, there are no known or published instances of green synthesis of AgNPs using *S. madagascariensis* (*S. mada*). *S. mada* is a native plant to Southern Africa [15] that has been used as a medicinal plant since ancient times. Around the globe, traditional medicine is currently being re-examined, and more studies on the medicinal qualities of plant species are being done [16, 17].

The most prevalent protein in the plasma is bovine serum albumin (BSA). This protein performs a wide range of physiological tasks, such as binding and transporting compounds like fatty acids, drugs, and other molecules [18]. Knowledge of how BSA interacts with nanoparticles is required to understand how the particles are absorbed and distributed in the biological systems which is crucial for pharmacological and pharmacodynamics understanding of the compounds [19, 20]. AgNPs are exposed to a

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variety of proteins in various quantities as they enter biological systems. AgNPs are easily protein-coated, creating an arrangement known as the protein ‘corona’ [21]. The biological identity of AgNPs, which differs from their synthetic identity, is altered by the protein corona, which also affects the particle size, aggregation state, and interfacial features of the AgNPs [22, 23]. This determines the fate of the AgNPs in biological media in vivo [24]. Therefore, it is important to study the interactions between proteins and AgNPs to better understand their biological effects and safety. In the present study, AgNPs were biosynthesized and capped using *S. mada.* leaves for potential use as a PTT agent. The binding mechanism and kinetics of the as-synthesized AgNPs with BSA were also studied to elucidate the biological response and interaction of the AgNPs with biological media.

Materials and methods

Materials

Silver nitrate (AgNO_3), bovine serum albumin (BSA, MW 66 kDa), phosphate buffered saline (PBS), and dimethyl sulfoxide (DMSO) were obtained from Sigma Aldrich with no further purification. Ultrapure water was used to make the required dilutions from the stock of BSA and PBS. The stock solution of BSA was prepared in 10 mM of PBS at pH 7.2. The plant extract *Senecio madagarensis* was identified and obtained from Lesotho. All the solvents used were analytical grade.

Energy-dispersive X-ray spectroscopy along with scanning electron microscopy (SEM) and EDX spectra have been obtained using a ZEISS EVOLS 15 scanning electron microscope. On a Bruker D8 Advance apparatus, powder X-ray diffraction (p-XRD) was carried out utilizing monochromatic Cu K ($\lambda = 1.5406 \text{ \AA}$, nickel filter) radiation in the 2θ scale range of 20° – 80° . A Perkin-Elmer Lambda 25 UV–Vis spectrophotometer was used to collect UV–Vis spectra, and a JEOL JEM 1400 TEM was used to capture TEM images.

Preparation of the plants

Plants were milled using a coffee machine and sequentially extracted after 24 h at room temperature. Extraction of *S. madagascariensis* is done using the infusion method, the powdered leaf extracts were placed in a beaker containing 200 mL of distilled water and boiled for 30 min [11]. The extracts were filtered after cooling using a Büchner funnel on Whatman No. 1 filter paper for further use.

Synthesis of AgNPs using *S. madagascariensis*

The preparation of AgNPs was done using a method adopted from previous study [12]. Different concentrations (20, 50, and 100 mM) of AgNO_3 were prepared. A (10 mL) extract of *S. mada.* was mixed for 10 min with 100 mL of AgNO_3 using a stirrer. The mixture was then heated for 2 h at 80°C and cooled. The solution was placed in a dark ambient for 24 h at room temperature. The color of the solution changed from colorless to green then eventually to brown to indicate the reduction of Ag(I) ions to Ag(0) nanoparticles. The obtained NPs were centrifuged at 5000 rpm for 20 min and washed with water and ethanol three times to remove impurities formed from the extract (Table S-1).

The interaction of BSA with AgNPs

The interaction of BSA and AgNPs was studied through steady-state fluorescence. The fluorescence spectra of BSA were recorded in the presence and absence of increasing concentrations of AgNPs. The BSA-PBS solution was made up of a phosphate-buffered saline (PBS) solution (pH 7.2). The AgNP stock solution was prepared in dimethyl sulfoxide (DMSO). The fluorescence emission spectra were recorded in the range 250–450 nm by exciting the solution at 280 nm with the excitation and emission slit width of 10. The fluorescence quenching constant was calculated using Eq. (1)

$$F_0/F = 1 + K_{SV}[Q] = 1 + k_q \tau_0 [Q] \quad (1)$$

where F_0 is the fluorescence intensity of the enzyme, F is the enzyme fluorescence intensity in the presence of the metal, K_{SV} is Stern–Volmer quenching constant, $[Q]$ is concentration of the quencher (metal complex), K_q is bimolecular quenching constant of the enzyme, τ_0 is the average lifetime of biomolecules in the absence of the quencher.

The K_{SV} values are obtained from the slope of the graph F_0/F vs $[\text{AgNP}]$. The quenching rate constant $k_q = K_{SV}/\tau_0$ ($\tau_0 = 10^{-8}$. Average lifetime of BSA-PBS without quencher). The data related to static and dynamic quenching mechanisms can be fitted into Eq. (5)

$$F_0/F = (1 + K_D[Q])(1 + K_S[Q]) = 1 + (K_D + K_S)[Q] + K_D K_S [Q]^2, \quad (2)$$

where K_D and K_S are the dynamic and static quenching.

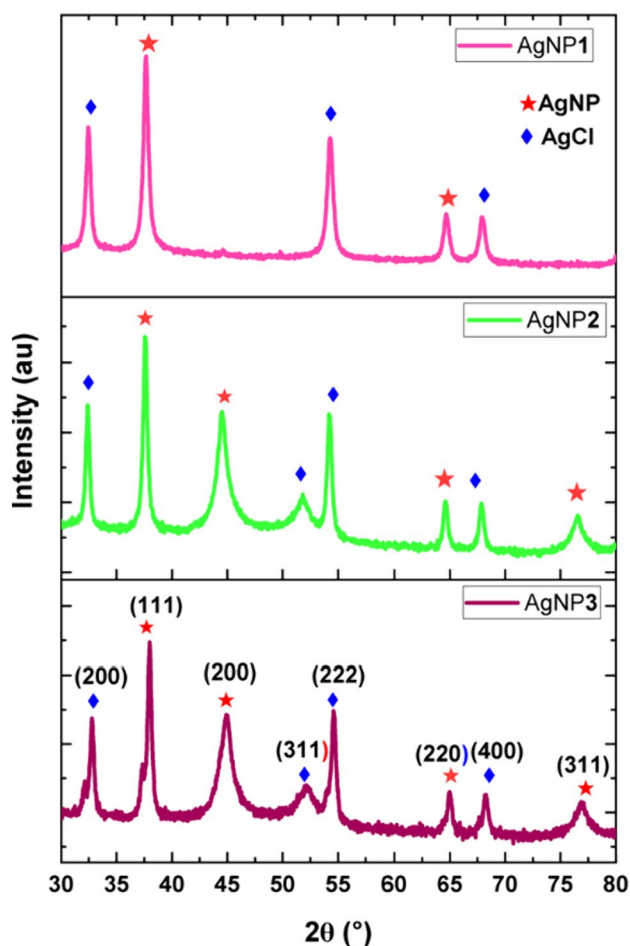


Fig. 1 Powder XRD diffraction patterns of *S. mada* synthesized Ag/AgCl nanoparticles

Results and discussion

Powder X-ray diffraction (XRD)

Powder X-ray diffraction was used to study the crystalline nature of the Ag/AgCl NPs (Fig. 1). Four distinct 2θ diffraction peaks observed at 38.05° , 44.9° , 64.9° , and 77.08° indexed at (111), (200), (220), and (311) indicated the formation of face-centered crystalline (FCC) structure of metallic silver (JCPDS 870597) [25]. In addition, strong diffraction peaks were observed at 32.7° , 52.15° , 54.63° , and 68.16° corresponding to crystalline planes of (200), (311), (222), and (400) of silver chloride, respectively [26]. The peaks show the FCC structure of silver chloride nanoparticles (AgCl NPs) and AgNPs for nanoparticles synthesized using 50 and 100 mM of the salt, however, nanoparticles synthesized using 20 mM comprised of the AgCl phase than the pure silver FCC crystalline phase.

These findings are in correlation with reports documented by other researchers which were elucidated by Okaiyeto

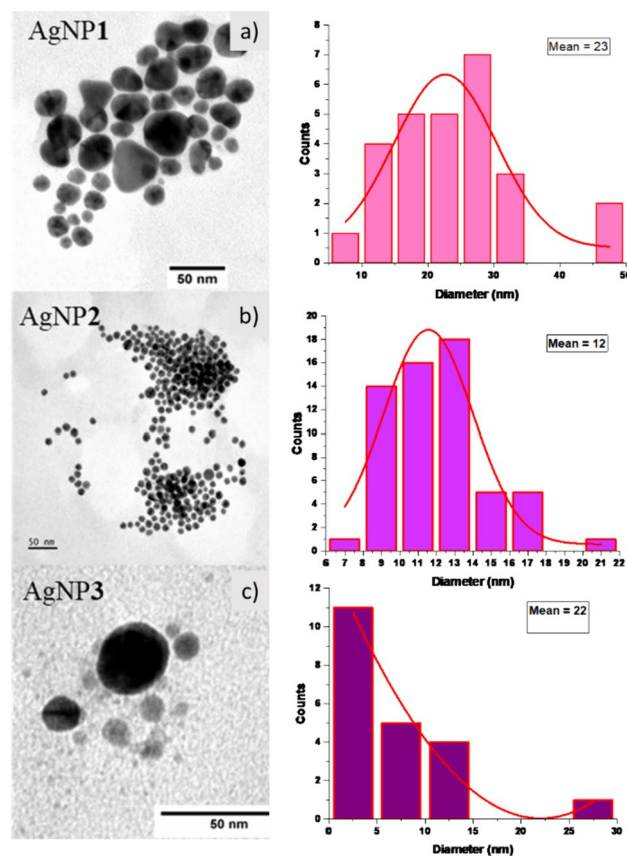


Fig. 2 TEM images of Ag/AgCl NPs synthesized using **a** 20 mM $\text{AgNO}_3(\text{aq})$, **b** 50 mM $\text{AgNO}_3(\text{aq})$, and **c** 100 mM $\text{AgNO}_3(\text{aq})$ and particle size distribution histogram

[13]. The initial stages of the synthesis of AgNPs involve the formation of AgCl. The reaction happens at room temperature, this is the reaction between Ag^+ from AgNO_3 and Cl^- from phytochemical compounds in the leaf extract. After the formation of AgCl, Ag^+ ions were reduced to metallic silver (Ag) by phytochemical compounds. Ag^+ was then combined with OH groups of phenolic compounds in the extract to probably produce an intermediate complex, which subsequently oxidized and reduced Ag^+ to Ag^0 [27]. The concentration (AgNO_3) may have influenced the nucleation and development of crystal nuclei, resulting in smaller silver nanoparticles. This idea appears to be supported by wider peaks for AgNPs but narrower sharper peaks for AgCl.

Morphological studies

The size and shape of the silver nanoparticles synthesized under various concentrations of AgNO_3 were examined using TEM microscopy. The results show that the prepared nanoparticles were spherical and quasi-spheroidal (non-uniform morphology), as depicted in Fig. 2. The average size measured from the TEM images was 23, 13, and 22 nm for

the AgNPs synthesized using 20, 50, and 100 mM of silver nitrate, respectively. The size of the nanoparticles decreased with the increase in the concentration of AgNO_3 . A higher concentration of silver nitrate results in a decreased ratio of the reducing agent to silver, which reduces the amount of plant molecules that cap the surface of the nanoparticle. Given that the plant molecules stop the nanoparticles from growing and aggregating, this results in smaller particle sizes. The biosynthesized nanoparticles were also evenly dispersed and showed no significant aggregation or morphological variations.

The SEM images (Fig. S-1) of the nanoparticles show rough surfaces morphologies for AgNP1 and AgNP2 with some hollow sphere in AgNP2 while AgNP3 surface morphology is smoother with some white patches. The presence of elemental carbon, oxygen, and chlorine peaks, as well as elemental silver metal, was seen in the EDX spectra of synthesized silver nanoparticles. Furthermore, the prominent peak at 3 keV verified the presence of characteristic peaks of metallic silver nanocrystals. The presence of both Ag and Cl confirms the synthesis of Ag/AgCl NPs as seen in Fig. S-1. Carbon, oxygen, and chlorine observed are assumed to be from the secondary metabolites of the plant. The percentage of Ag was in the range of 64.0, 69.5, and 72.5% for AgNP1, AgNP2, and AgNP3 nanoparticles synthesized with 20, 50, and 100 mM. The results show that increase in the salt concentration also resulted in increase in the percentage of silver in the nanoparticles.

Optical studies of the plant-mediated Ag/AgCl nanoparticles

Figure S-2 shows the UV–Vis of Ag/AgCl NPs synthesized using 20, 50, and 100 mM of the silver salt. The results indicate that when the concentration of AgNO_3 increases, the absorption intensity increases, resulting in the synthesis of more Ag nanoparticles. The absorption spectra indicated that as the concentration of the silver salt increased from 20 to 100 mM, the absorption band edges of the nanoparticles shifted from 415 to 411 nm which could be ascribed to the formation of smaller nanoparticles as the concentrations of the metal salt increases. This may mean that at higher concentrations, the reactants nucleate slower with slower growth rates which results in the formation of smaller nanoparticles. The interaction between the biomolecules in the green synthesis method and the silver ions drives the nucleation of silver nanoparticles and this is not universal but rather depends on the secondary molecules in the plant extract. The results are in agreement with a study conducted using an aloe vera extract where an increase in the concentration of AgNO_3 resulted in smaller and monodisperse nanoparticles [28]. The optimum concentration of AgNO_3 for the synthesis of the nanoparticles was deemed to be 50 mM showing a

characteristic SPR band for Ag/AgCl NPs with monodispersity. The appearance of bands at 665 and 668 is due to the formation of other shapes of nanoparticles which absorb at higher wavelengths.

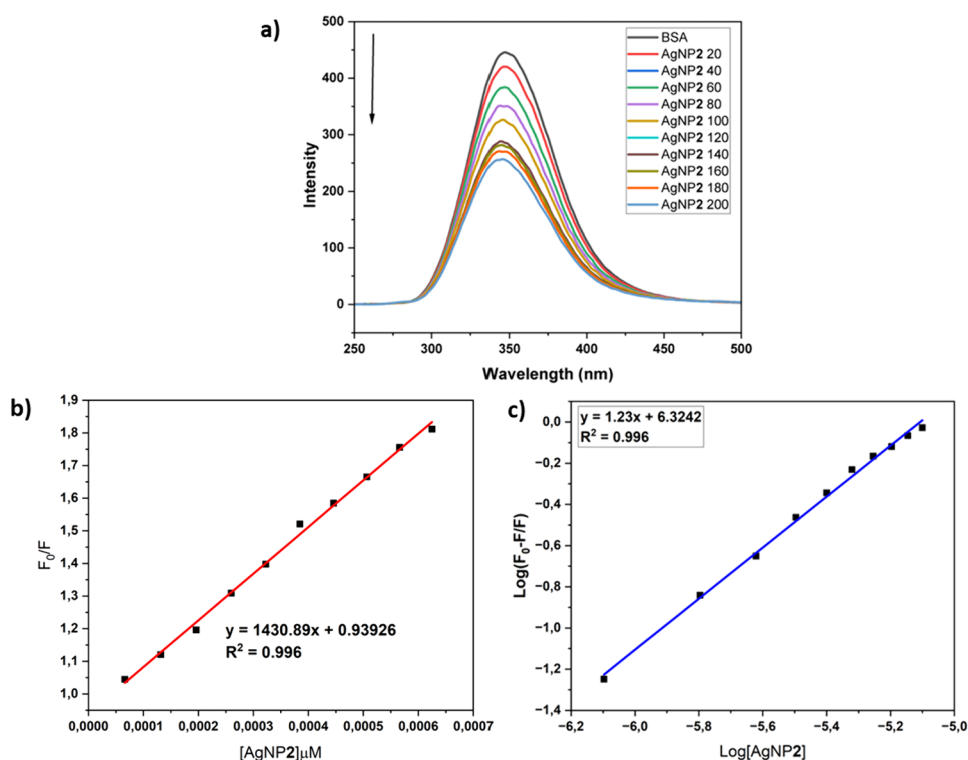
These results suggest that, on average, the number of synthesized Ag nanoparticles reduces as the energy band gap of silver nanoparticles increases Fig. S-2b. This effect is a result of quantum mechanics; as materials size increases, the outer electronic orbitals of the participated atoms overlap with the conduction band and hence possess more energy. As a result of this occurrence, the gap between the valence band and conduction decreases. The band gap energy using 20 mM silver nitrate is 2.71 eV, for nanoparticles synthesized with 50 mM AgNO_3 , 2.73 eV and at 100 mM of AgNO_3 , 2.66 eV. The band gap energy of the nanoparticles increased with increased silver salt concentration. However, the decrease at higher concentration (100 mM) may be due to the increase particle size of the nanoparticles observed on the TEM images (Fig. 2). Consequently, it is observed that the band gap energy decreased with Ag/AgCl particle size.

FTIR was utilized to identify the involvement of biomolecules in the bioreduction of the silver(I) and the stability of the as-synthesized Ag/AgCl NPs (Fig. S-3). The FTIR spectra of *S. mada*-AgNPs shows a broad peak at 3315 cm^{-1} which is characteristic of the O–H stretching for alcohols in the phenols. The prominent peaks at 3057 cm^{-1} are attributed to the N–H asymmetric stretching vibration of the amide groups from the plant extract. The absorption bands at 1705 cm^{-1} are due to the amide C=O of carbonyls while the band at 1079 cm^{-1} is assigned to the C–O stretching vibrations. The strong band at 731 cm^{-1} is assigned to the C–Cl stretching of the alkyl chloride. The dual significance of biological molecules in the synthesis and stability of the AgNPs is confirmed by the FTIR (Fig. S-3).

Interaction of BSA in the presence of AgNPs The binding studies of AgNP with BSA

A comprehensive tool to study proteins and nanoparticles binding is the fluorescence emission spectroscopic approach. The results could be used to understand the polarity shifts around the fluorophores. The aromatic fluorophores that produce spectra are the residues of the amino acids tyrosine (Tyr), tryptophan (Trp), and phenylalanine (Phe). Among these residues, tryptophan (Trp) is the most sensitive to changes in the microenvironment and exhibits the highest fluorescence intensity [29]. The fluorescence emission spectral analysis was done to study the effect of increase in concentrations of AgNPs on the BSA emission intensity. The fluorescence spectra are shown in Fig. 3. The emission spectra show the quenching of the intensity of BSA with increase in concentration of the AgNPs. The gradual quenching in fluorescence intensity indicates

Fig. 3 **a** The Fluorescence quenching spectra of BSA in the presence and absence of varying concentrations of AgNP, **b** Stern–Volmer plot of BSA and AgNPs and **c** a plot of $\log(F_0 - F/F)$ vs $\log[Q]$. Equation 3 was used to compute the Stern–Volmer quenching constant (K_{SV}) and various quenching mechanism parameters



the formation of a complex between BSA and AgNPs. Numerous mechanisms, including molecular interactions, molecular arrangements, complex formation, and energy transfer, are involved in quenching [30]. The change in the intrinsic emission intensity of bio-macromolecules is correlated with interactions between nanoparticles and proteins, and AgNPs are known to have strong quenching potential toward numerous chromophores [31]. The excitation wavelength of the compounds was set to 280 nm with an emission from 250 to 450 nm. The maximum emission from the spectra was 432.52 nm with a slight redshift as the concentrations of AgNP increased. Fluorescence quenching can be divided into dynamical and static mechanisms; the former includes the collision of the fluorophore and the quencher in the fluorophore's excited state, while the latter results from the synthesis of the fluorophore–quencher complex in the ground state [32].

$$F_0/F = 1 + K_{SV}[Q] = 1 + k_q \tau_0 [Q] \quad (3)$$

where F_0 and F are fluorescence intensities of BSA in the absence and presence of a quencher respectively. K_{SV} is the Stern–Volmer constant, $[Q]$ is the concentration of the quencher, k_q is the quenching rate constant τ_0 is the average fluorescence lifetime of the protein fluorophores in the absence of the quencher. Figure 3b shows the Stern–Volmer plot between F_0/F and $[AgNP]$. The K_{SV} value obtained from the slope of the Stern–Volmer plot

was $1.4309 \times 10^3 \text{ L mol}^{-1}$. In addition, k_q was obtained as $1.43 \times 10^{11} \text{ L mol}^{-1} \text{ s}^{-1}$, this suggests that the silver nanoparticle quenching of the fluorophore of the BSA was through a static quenching mechanism. The results demonstrated that AgNPs had a strong ability to quench BSA's fluorescence intensity.

The estimation of binding parameters and binding energy

Further analysis of the fluorescence quenching data allowed for the determination of other binding characteristics, such as binding constants (K_b) and the number of binding sites (n), using Eq. (4).

$$\log F_0 - F/F = \log K_b + n \log [Q], \quad (4)$$

The values of K_b and n were obtained from the plot of $\log(F_0 - F/F)$ vs $\log[Q]$ in Fig. 3c. At room temperature, the BSA–NPs interaction's n value is close to 1, which suggests that there is just one binding site for NPs on BSA. The computed value K_b is in the range of 10^6 , which supports the existence of AgNPs and BSA's strong binding interaction. Equation 5 was used to calculate the value of ΔG .

$$\Delta G = -RT \ln K_b. \quad (5)$$

The spontaneity of the binding process is shown by the negative value of ΔG (Table S-2).

Conclusion

A facile method to prepare Ag/AgCl NPs using *S. madagascariensis* plant extracts (leaf) and the binding interactions between the nanoparticles and BSA is presented in this study. Increase in the concentration of AgNO₃ resulted in a decrease in the particle size of the as-synthesized nanoparticles. The silver nanoparticles were well dispersed, spherical in shape, and ranged in size from 13 to 25 nm. The band gaps of the nanoparticles increased with an increase in the concentration of the salt from 2.71 eV for the smallest concentration to 2.73 eV in higher concentrations. Powder XRD diffraction patterns confirmed silver nanoparticles with a face-centered cubic lattice crystal structure of Ag and AgCl. FTIR analysis of the *S. mada.* shows interactions of the hydroxyl, carbonyl, and amine groups with the Ag/AgCl NPs as capping and stabilizing agents. The nanoparticles synthesized using 50 mM of AgNO₃ showed monodispersed and smaller particles and were hence deemed to be the ideal concentration for the preparation of Ag/AgCl NPs using *S. madagascariensis*. The findings suggested that the interaction of AgNPs with BSA may be a static quenching process and that the process is spontaneous with hydrogen bonding and hydrophobic interactions functioning as the main active forces with one binding site. Due to the negative sign of the ΔG , this indicated that the binding was spontaneous.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1557/s43580-024-00826-z>.

Author contributions NH carried out experiments, formal analysis, and writing the manuscript's draft. SPS and were responsible for conceptualization, funding acquisition, supervision of draft writing, review, and final editing. All authors review the manuscript and approve for submission to the journal.

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Data availability All data obtained in the course of the study are included in the manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest.

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References

1. R. Amatya et al., BSA/silver nanoparticle-loaded hydrogel film for local photothermal treatment of skin cancer. *Pharm. Res.* **38**, 873–883 (2021)
2. A. Aygenur et al., Biological synthesis of silver nanoparticles using *Rheum ribes* and evaluation of their anticarcinogenic and antimicrobial potential: A novel approach in phytanotechnology. *J. Pharm. Biomed. Anal.* **179**, 113012 (2020)
3. M. Bhagat et al., Green synthesis of silver nanoparticles using aqueous extract of *Rosa brunonii* Lindl and their morphological, biological and photocatalytic characterizations. *J. Inorg. Organomet. Polym.* **29**, 1039–1047 (2019)
4. A. Salleh et al., The potential of silver nanoparticles for antiviral and antibacterial applications: A mechanism of action. *Nanomaterials* **10**(8), 1566 (2020)
5. N. Tehri et al., Biosynthesis, antimicrobial spectra and applications of silver nanoparticles: Current progress and future prospects. *Inorg. Nano-Met. Chem.* **52**(1), 1–19 (2022)
6. S. Some et al., Biosynthesis of silver nanoparticles and their versatile antimicrobial properties. *Mater. Res. Express.* **6**(1), 012001 (2018)
7. R.H. Ahmed et al., Green synthesis of silver nanoparticles mediated by traditionally used medicinal plants in Sudan. *Int. Nano. Lett.* **10**(1), 1–14 (2020)
8. N. Manosalva et al., Green synthesis of silver nanoparticles: Effect of synthesis reaction parameters on antimicrobial activity. *World J. Microbiol. Biotechnol.* **35**, 1–9 (2019)
9. M.A. Huq, Green synthesis of silver nanoparticles using *Pseudoduganella eburnea* MAHUQ-39 and their antimicrobial mechanisms investigation against drug resistant human pathogens. *Int. J. Mol. Sci.* **21**(4), 1510 (2020)
10. F.A. Alharbi et al., Green synthesis of silver nanoparticles from *Neurada procumbens* and its antibacterial activity against multi-drug resistant microbial pathogens. *J. King Saud Univ. Sci.* **32**(2), 1346–1352 (2020)
11. J. Qu et al., Anti-human gastric cancer study of gold nanoparticles synthesized using *Alhagi maurorum*. *Inorg. Chem. Commun.* **151**, 109859–91 (2023)
12. K. Chandhirasekar et al., Plant-extract-assisted green synthesis and its larvicidal activities of silver nanoparticles using leaf extract of *Citrus medica*, *Tagetes lemmonii*, and *Tarenna asiatica*. *Mater. Lett.* **287**, 129265 (2021)
13. R. Erenler et al., Green synthesis of silver nanoparticles using *Stachys spectabilis*: Identification, catalytic degradation, and anti-oxidant activity. *BBRC* **659**, 91–95 (2023)
14. A.S. Alqahtani et al., In vitro antioxidant, cytotoxic activities, and phenolic profile of *Senecio glaucus* from Saudi Arabia. *ECAM* **2020**, 8875430 (2020)
15. K. Wijayabandara et al., Review of the biology, distribution, and management of the invasive fireweed (*Senecio madagascariensis* Poir). *Plants* **11**(1), 107 (2021)
16. B. Morejon et al., Larvicidal activity of silver nanoparticles synthesized using extracts of *Ambrosia arborescens* (Asteraceae) to control *Aedes aegypti* L. (Diptera: Culicidae). *J. Nanotechnol.* **2018**, 6917938 (2018)

17. S. Chatterjee et al., Green synthesis and characterization of silver nano-conjugates using some common medicinal weeds leaf aqueous extracts. *IJPSN*. **13**(1), 4752–4758 (2020)
18. A. Saha et al., Fatty-amine-conjugated cationic bovine serum albumin nanoparticles for target-specific hydrophobic drug delivery. *ACS Appl. Nano Mater.* **2**(6), 3671–3683 (2020)
19. G. Wang, C. Yan et al., Surface chemistry of gold nanoparticles determines interactions with bovine serum albumin. *Mater. Sci. Eng. C* **103**, 109856 (2019)
20. M.A. Siddiquee, M. ud din Parray, S.H. Mehdi, K.A. Alzahrani, A.A. Alshehri, M. Malik et al., Green synthesis of silver nanoparticles from *Delonix regia* leaf extracts: In-vitro cytotoxicity and interaction studies with bovine serum albumin. *Mater. Chem. Phys.* **242**, 122493 (2020)
21. Z. Zhao et al., Identification and interaction mechanism of protein corona on silver nanoparticles with different sizes and the cellular responses. *J. Hazard. Mat.* **414**, 125582 (2021)
22. R. Barbir et al., Protein corona modulates distribution and toxicological effects of silver nanoparticles in vivo. *Part. Part. Syst. Charact.* **36**(8), 1900174 (2019)
23. N.A. Azman et al., Dynamics of human serum albumin corona formation on gold nanorods with different surface ligands in silico. *J. Phys. Chem. B* **125**(4), 1181–1195 (2021)
24. M. Barbalinardo et al., Surface properties modulate protein corona formation and determine cellular uptake and cytotoxicity of silver nanoparticles. *Nanoscale* **13**(33), 14119–14129 (2021)
25. T. Gan et al., Facile synthesis of monodisperse Ag@C@Ag core double shell spheres for application in the simultaneous sensing of thymol and phenol. *New J. Chem.* **39**(8), 6244–6252 (2015)
26. M.S. Al Aboody, Silver/silver chloride (Ag/AgCl) nanoparticles synthesized from *Azadirachta indica* latex and its antibiofilm activity against fluconazole resistant *Candida tropicalis*. *Artif. Cells Nanomed. Biotechnol.* **47**(1), 2107–2113 (2019)
27. S. Al-Zahrani et al., Role of synthetic plant extracts on the production of silver-derived nanoparticles. *Plants* **10**(8), 1671 (2021)
28. C. Vanlalveni et al., Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: A review of recent literature. *RSC Adv.* **11**(5), 2804–2837 (2021)
29. G. Wang et al., Probing the binding behavior and kinetics of silver nanoparticles with bovine serum albumin. *RSC Adv.* **7**(15), 9393–9401 (2017)
30. M. Waghmare et al., Multiple layer formation of bovine serum albumin on silver nanoparticles revealed by dynamic light scattering and spectroscopic techniques. *J. Nano Res.* **20**, 1–2 (2018)
31. S. Hamed et al., Evaluation of the catalytic, antibacterial and anti-biofilm activities of the *Convolvulus arvensis* extract functionalized silver nanoparticles. *Photochem. Photobiol. B Biol.* **167**, 36–44 (2017)
32. E. Munoz et al., Interaction between nitroxyl radicals and CdTe quantum dots: Determination of fluorescence-quenching mechanisms in aqueous solution. *J. Photochem. Photobiol. Biol.* **383**, 112024 (2019)

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