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Ag colloids and Ag clusters over EDAPTMS-coated silica nanoparticles: synthesis, characterization, and antibacterial activity against *Escherichia coli*

Shiva K. Rastogi, PhD*, Veronica J. Rutledge, BS, Charlene Gibson, BS, David A. Newcombe, PhD, Josh R. Branen, PhD, and A. Larry Branen, PhD

Biosensors and Nanotechnology Application Laboratory (BNAL), University of Idaho, Coeur D'Alene, Coeur d'Alene, Idaho, USA

Abstract

To produce better antibacterial water-insoluble nanocomposites of silver (Ag), silver–silicon dioxide (Ag-SiO₂) hybrid and silver colloid (Ag-c) nanoparticles (NPs) were studied. Ag-c NPs were synthesized using reduction of AgNO₃, and Ag-SiO₂ composites were prepared on a core of silica NPs functionalized with ethylenediamino-propyltrimethoxysilane, where Ag clusters were fabricated on amino groups using seed-mediated growth and characterized by transmission electron microscopy and ultraviolet-visible absorption spectroscopy. Antibacterial effectiveness of the Ag-SiO₂ NPs was tested against general *Escherichia coli* (*E. coli* ATCC 25922) and *E. coli* O157:H7 by measuring the growth based on optical density and digital counting of live-dead cells using a fluorescent microscope, and a field emission scanning electron microscope. Minimum inhibitory concentration values were studied against four representative bacteria along with *E. coli* O157:H7. Results showed that Ag NPs of 6.6 ± 4.5 nm were attached to the surface of SiO₂ NPs (74 ± 13.5 nm), and the Ag-c NPs (3.5 ± 2 nm) showed excellent antibacterial properties.

Keywords

Ag-SiO₂ nanoparticles; Ag colloids; Transmission electron microscopy; Field emission scanning electron microscopy; Optical density; Antibacterial

The antibacterial property of silver (Ag) has been known for thousands of years, and the ancient Greeks cooked in silver pots. The adage, “born with a silver spoon in his mouth” referred to more than simply wealth, and it was well known that eating with a silver spoon was more hygienic.¹ Currently, the investigation of this phenomenon has gained importance as a result of the increase in bacterial resistance to antibiotics.² Silver nanoparticles (Ag NPs)³ as well as various silver-based compounds and materials containing ionic silver (Ag⁺)⁴ or metallic silver (Ag⁰)⁵ have recently been synthesized and shown to exhibit antimicrobial activity against several species of bacteria including *Escherichia coli*.⁶

E. coli inhabit the intestines of humans and other animals. Although most strains of *E. coli* are not pathogenic, *E. coli* O157:H7 produces Shiga-like toxin and causes diarrhea and abdominal cramps,⁷ and is considered as the most pathogenic strain of *E. coli*. Outbreaks of *E. coli* O157:H7 infection have been associated with the consumption of foods of animal origin, such as undercooked beef,⁸ improperly pasteurized milk,⁹ or contaminated water.¹⁰ It

is estimated that these bacteria cause thousands of foodborne illnesses and hundreds of hospitalizations and deaths worldwide each year.¹¹ It is very important to monitor pathogenic *E. coli* strains and stop their growth by simple and novel means.

Antibacterial activity of silver-containing compounds has been widely used to reduce infections in burn treatment¹² and arthroplasty,¹³ as well as to prevent bacteria colonization on prostheses,¹⁴ catheters,¹⁵ and human skin.¹⁶ Silver ions have also been coated onto stainless-steel materials for use in the food industry¹⁷ and water treatment.¹⁸ The antimicrobial activity of silver colloids (Ag-c) is influenced by the dimension of the particles, with smaller particles showing greater antimicrobial effect.¹⁹

Therefore, in developing the route of synthesis, an emphasis was made to control the size (<10 nm) of Ag NPs. Ag NPs alone in solution easily aggregate, resulting in deterioration of their chemical properties and a loss of their antibacterial properties.²⁰ To solve these problems we synthesized Ag NPs linked with a diamino group (ethylenediamino-propyltrimethoxysilane; EDAPTMS) onto silica NPs (Ag-SiO₂) using a modified seed-mediated growth method. Silica particles provide high surface area for surface functionalization, give excellent mechanical strength for supporting Ag NPs, offer thermal stability, and are inexpensive.²¹ SiO₂ has been used previously to grow Ag NPs for improving antibacterial properties of Ag and SiO₂ composites. Kim et al²⁰ have grafted Ag NPs directly onto SiO₂ NPs with and without using catalyst ammonia solution, and Gao et al²¹ used quaterized polyethyleneimine-grafted SiO₂ NPs.

In our study EDAPTMS was used for surface functionalization of SiO₂ NPs to produce a functional composite of silica particles with high nucleophilic properties. Our laboratory is focused on developing low-cost, water-insoluble antibacterial materials for monitoring and improving water quality. Thus, we grafted Ag NPs with EDAPTMS-functionalized SiO₂ NPs and studied their antibacterial activity against five different representative bacterial strains as compared to Ag-c NPs²² in aqueous culture media.

Methods

Materials

All the reagents were purchased from Sigma-Aldrich (St. Louis, Missouri), Fisher Scientific (Somerville, New Jersey), and Invitrogen Molecular Probes (Eugene, Oregon), and used without any further purification. Luria Bertani (LB) medium and agar were purchased from EMD Chemicals, Darmstadt, Germany. *E. coli* strain ATCC 25922 (general strain) and *E. coli* O157:H7 bovine strains were provided by Dr. Gregory Bohach (University of Idaho, Moscow); *Pseudomonas aeruginosa* ATCC 27853 and *Salmonella enterica* ATCC 19585 were obtained from American Type Culture Collection (ATCC; Manassas, Virginia), and *Bacillus cereus* was obtained from the University of Idaho teaching laboratory for use in this study. Phosphate-buffered saline (PBS) was prepared from a 10× autoclaved stock (10× PBS: 100 mM phosphate buffer, 1.37 M NaCl, 27 mM KCl, pH 7.2. Deionized water (DI; 18.2 MΩ) was collected from Labconco, water Pro PS (Labconco, Kansas City, Missouri).

Instrumentation

A JEOL 1200EX II model (JEOL, Tokyo, Japan) was used for transmission electron microscopy (TEM) images, and a Supera Gemini 35 VP Field Emission-Scanning Electron Microscope (Zeiss, Oberkochen, Germany) coupled with a Thermoelectron (Zeiss) model was used for field emission scanning electron microscopy (FE-SEM) imaging. The functional group of the nanoparticles was characterized using an ultraviolet-visible (UV-vis) spectrophotometer model Pharma-Spec UV-1700 (Shimadzu, Tokyo, Japan). Bacterial growth was monitored using a Beckman Coulter LD 400 luminometer (Beckman Coulter,

Fullerton, California) along with AD LD analysis software version 1.6 (VWR International, West Chester, Pennsylvania). Bactericidal effects were characterized using a Leitz LaborLux S microscope (VWR International, West Chester, Pennsylvania) with a Leica EC3 objective head and camera (Leica Microsystems Inc., Bannockburn, Illinois) and a Leo fluorescent Lamp (VWR International, West Chester, Pennsylvania). All glassware was cleaned with aqua-regia and rinsed with ethanol and DI water several times before use.

Synthesis of Ag-SiO₂ and Ag-c NPs

The Ag-SiO₂ NPs were synthesized from their monomer precursor, tetraethoxysilane, using a slightly modified seed-mediated growth method.²³ The silica NPs were prepared by mixing 3.0 mL of 28–30% (vol/vol) ammonium hydroxide solution, 0.5 mL DI water, and 50.0 mL of ethanol. The silica precursor (1.5 mL of tetraethoxysilane) was added to the above solution dropwise (50 µL/min) over 30 minutes and stirred at 1200 rpm overnight at room temperature (RT, 20–22°C). As the silica NPs formed, the solution became opaque. Then SiO₂ NPs were separated using centrifugation at a speed of 4000 rcf and washed with ethanol three times. This was followed by suspending the NPs in 50 mL of ethanol and treating with 5% EDAPTMS for surface functionalization.²⁴ The reaction mixture was stirred at RT for 4 hours and refluxed for 1 hour at 80°C; then 0.5 mL of 1% (wt/vol) sodium citrate (Na₃C₆H₅O₇) solution and 500 µL of 0.05 M AgNO₃ were added dropwise. The reaction mixture was stirred for 1 hour, and the color changed from opaque to light brown. The NPs were separated from solution by centrifuging at 4000 rcf for 30 minutes and washed three times with 50% (vol/vol) ethanol/water. The NPs were then dried overnight in vacuum desiccators and cured at 110°C for 12 hours in a conventional oven. NPs were cooled to RT and stored at 4°C.

The Ag-c NPs were prepared in our laboratory as reported by Reddy et al.²⁵ Briefly, 5 mL of a 5 mM AgNO₃ solution were added to 20 mL of water giving 25 mL of a 1 mM AgNO₃ solution. The solution was placed in a 50-mL conical flask and stirred at 1200 rpm and heated until it began to boil. Then, 1 mL of 1% (wt/vol) sodium citrate solution was added at once. Vigorous stirring and heating continued until a color change to pale yellow was visible (at 3.5 minutes). The solution was then removed from the heating plate but stirring continued while cooling to RT. The solution was topped with water up to 25 mL to account for boiling losses. The pale yellow solution was stored at 4°C.

The presence of Ag NPs on Ag-SiO₂ NPs was confirmed using UV-vis absorbance spectrometry. Size distribution and morphology of Ag-SiO₂ and Ag-c NPs were characterized using TEM imaging.

Bacterial growth-inhibiting effect in LB broth using turbidity

E. coli strains were cultured on LB agar plates for 18 hours at 37°C before use. Differing concentrations of Ag-c and Ag-SiO₂ NPs were prepared in sterilized LB medium in a final volume of 10 mL. The growth of bacteria was monitored with and without Ag-c at concentrations of 0.085, 0.85, 8.5, 17, 34, 42.5 µg/mL, and Ag-SiO₂ NPs at 0.1, 1, 10, and 100, µg/mL. A single colony of *E. coli* was used for inoculating the LB medium containing the NPs as well as a positive control containing only bacteria without Ag-c NPs. Aliquots were taken every hour up to 9 hours and then after 24 hours for measurement of the optical density (OD) at 620 nm.

Bacterial growth-inhibiting effect based on LB agar plating

The growth-inhibiting effects of Ag-c and Ag-SiO₂ NPs were further confirmed by plating on LB agar plates after 24 hours of growth at 37°C in LB broth. Serial dilutions of these mixtures were made in PBS up to 10⁻⁹ concentration and then plated on LB agar plates.

Samples containing only bacteria were plated as positive controls. The LB broth containing *E. coli* and NPs was diluted based on the growth that was observed through OD readings. The plates were incubated at 37°C for 24 hours followed by counting the number of colonies on the plate and calculating the increase in colony-forming units (cfu) per milliliter according to the following formula²⁶: $[(\text{Viable count at 0 hours} - \text{Viable count at 24 hours}) / \text{Viable count at 0 hours}] \times 100\%$.

Bactericidal effect using live/dead cell staining

Experiments were carried out in the presence and absence of silver NPs to determine the cell viability of *E. coli* and *E. coli* O157:H7 bacteria by using the BacLight²⁷ bacterial viability kit (Invitrogen, Carlsbad, California). *E. coli*-inoculated LB broth with and without Ag-SiO₂ or Ag-c NPs was incubated at 37°C for 24 hours. The samples were centrifuged at 3500 rcf for 10 minutes so as to pellet the cells and then rinsed three times with 1 mL sterile 0.85% NaCl solution. After the final rinse the cells were resuspended in 1 mL 0.85% NaCl solution, and 1 µL of each of reagents A and B from the kit were added. The suspension was incubated at RT for 15 minutes followed by filtration onto a 25-mm black polycarbonate filter, so as to concentrate the cells. The filter was then placed onto glass microscope slides with coverslips and visualized under a fluorescent microscope using red and green filters for analysis. The dead cells were counted using a red filter, and the live cells were counted using the green filter.

Antibacterial test

The antimicrobial activity of Ag-SiO₂ and Ag-c NPs was tested using the standard microdilution method,²⁸ which determines the minimum inhibitory concentration (MIC) leading to the inhibition of bacterial growth. Five different bacteria (*E. coli* ATCC 25922, *E. coli* O157:H7, *Pseudomonas aeruginosa* ATCC 27853, *Salmonella enterica* ATCC 19585, and *Bacillus cereus*) were tested at a concentration of $\sim 10^7$, 10^7 , 10^8 , 10^5 , and 10^6 cfu/mL, respectively. Bacteria were grown on LB agar broth with five different concentrations of Ag-SiO₂ (10, 50, 75, 100, 125 µg/mL) and Ag-c (8.5, 17.0, 34, 42.5, 85 µg/mL). The samples were incubated for 24 hours at 35°C, and then 100-µL samples were placed on nutrient agar plates. The MIC values were read after 24 hours of incubation at 35°C.

Results

Characterization of the synthesized Ag-SiO₂ and Ag-c nanoparticles

The Ag-SiO₂ NPs used in this study were imaged by TEM (Figure 1, A–D). The shape of these silica NPs was nearly spherical, and their average diameter (Figure 1, F) was 73.53 ± 13.47 nm. The silver particles linked to the surface of SiO₂ NPs (Figure 1, A–D) are also nearly spherical in shape with a mean size of 6.6 ± 4.5 nm (Figure 1, G). The TEM image of Ag-c NPs (Figure 1, E) showed an average size of about 3.5 ± 2.2 nm (Figure 1, H). Analysis of the TEM images of both particles reveals that the average sizes of Ag NPs, both free and on the surface of SiO₂, are in the nanometer range.

The prepared aqueous solution of Ag-SiO₂ and Ag-c NPs shows an absorption peak at 390–420 nm in the UV-vis spectrum (Figure 2, A and B, respectively). This is a typical absorption band of crystalline spherical Ag NPs²⁹ and is due to their surface plasmon.³⁰ The stability of a concentrated solution was checked by observing the absorption spectrum after serial dilutions ranging from five to seven times. The absorption spectrum of the diluted NPs is almost identical to the spectral features of a concentrated solution of Ag-SiO₂ NPs. This confirms that the Ag-SiO₂ NPs are not further dimerized or agglomerated.³¹ However, in the case of Ag-c NPs solutions the absorption spectrum at higher concentrations is different

from solutions of lower concentration, which indicates that there are some particles that are dimerized or agglomerated.

Antibacterial activity of Ag-SiO₂ and Ag NPs against *E. coli*

The different concentrations of Ag-SiO₂ and Ag-c NPs were mixed with *E. coli* in culture tubes and incubated 24 hours at 37°C. Bacterial growth was totally suppressed in the presence of both kinds of Ag NPs (Figure 2, C and D). This was confirmed by plating a diluted aliquot from each tube onto a nutrient agar plate and observing after incubation for 24 hours at 37°C. Bacterial growth in the presence of Ag-SiO₂ NPs (Figure 2, E) and controls and in the presence of Ag-c NPs shows the same results (Figure 3, F).

To test the antibacterial effectiveness of these NPs against general *E. coli* and *E. coli* O157:H7, the OD was measured in LB broth in the presence and absence of NPs. A level of 8.5 or 42.5 µg/mL of Ag-c NPs totally inhibited the growth of the general strain of *E. coli* throughout the 24-hour period of incubation (Figure 3, A). Limited inhibition was observed at 8.5 µg/mL. The Ag-SiO₂ NPs at 10 µg/mL inhibited the growth of the general *E. coli* strain up to 6 hours, whereas 100 µg/mL was effective throughout the 24-hour incubation and totally prevented growth (Figure 3, B). As is noted, 100 µg/mL Ag-SiO₂ NPs control did result in a high initial turbidity, but there was no apparent change over time, indicating inhibition of bacterial growth. In tests against *E. coli* O157:H7, the higher concentrations of Ag-c (42.5 µg/mL) and Ag-SiO₂ (100 µg/mL) NPs also inhibited the growth up to 24 hours (Figure 3, C and D, respectively). The complex of *E. coli* and Ag-SiO₂ NPs was analyzed using FE-SEM imaging (Figure 4, C and D).

Plate counts were also used to monitor growth of the general strain of *E. coli* at the end of the 24-hour incubation. The inhibitory effects observed using turbidity were confirmed using plate counts. It should be pointed out that the samples with NPs were diluted before plating; however, the NPs were still present in the plates and thus probably influenced growth on the plates. Concentrations of 5 and 10 µg/mL of Ag-SiO₂ and 8.5 µg/mL Ag-c NPs reduced growth of *E. coli* on the plates, but no growth was observed at 100 µg/mL of Ag-SiO₂ and at 42.5 µg/mL of Ag-c NPs (Figure 4, A and B, respectively). These results confirm that the synthesized Ag-SiO₂ NPs have antibacterial effectiveness similar to Ag-c NPs.

Live-dead monitoring of bacterial cells

The fluorescence images of the stained bacterial cells were taken using a microscope with a green filter (535 nm) used for visualizing live cells and a red filter (642 nm) used for dead cells (Figure 5, A–L). All the fluorescent images were captured from a single spot of each sample by flipping the red and green filter set, which gives reliable digital counting of cells.

The digital counting of live vs. dead bacterial cells was expressed as the function of percentage, and results are the mean of three images. In the presence of 100 µg/mL of Ag-SiO₂ NPs, 74% of the general strain were killed, whereas 64% of *E. coli* O157:H7 were killed (Figure 6, A and B). Ag-c NPs at 8.5 µg/mL showed similar results, with a 70% death of the general strain and 60% death of *E. coli* O157:H7.

The MIC values of synthesized Ag-SiO₂ and Ag-c NPs are shown in Table 1 against five different bacteria.

Discussion

We prepared silica NPs using a variation of the method developed by Stöber et al³² with the surface functionalized with EDAPTMS. The TEM analysis (Figure 1, A–D) clearly shows

attachment of Ag NPs on SiO₂, and the Ag-SiO₂ composites were observed individually as well as in small aggregates. In our previous study we reported that the surface functionalization of silica NPs with amino-propyltrimethoxysilane (APTMS) was useful for linking with fluorescein dye.³³ The premodification of silica with EDAPTMS provides two nucleophilic (amino) groups that immobilize the metallic silver particles on the surface of silica particles. Thus, silver NPs of small size were tethered to the EDAPTMS-functionalized silica surface by virtue of the aminophilic nature of silver particles. These small colloidal particles coordinate to lone pairs of the primary and secondary amino groups of EDAPTMS, which stabilizes the Ag NPs on the surface of silica. As is well known, the alkyl-amines exist predominantly as positive-charged R-NH³⁺ groups when the value of pH is below 10 (Ref. [34]), and the reduction of Ag⁺ with excess sodium citrate afforded small silver particles with a net negative interfacial charge.³⁵ Due to electrostatic repulsive force, the silver particles immobilized on the surface are separated, as is shown in the TEM image of Ag-SiO₂ particles.

The OD graph and agar plate readings of well-dispersed Ag-c NPs at 42.5 µg/mL and Ag-SiO₂ at 100 µg/mL shows similar antibacterial effectiveness in LB broth against *E. coli* ATCC 25922 and *E. coli* O157:H7. The mechanism of antibacterial property of Ag NPs has been well established by free-radical generation from Ag NPs using electron spin resonance spectroscopy,³¹ and O-Ag vibration at 206–232 cm⁻¹ and ionic species adsorbed onto Ag NPs were observed using surface-enhanced Raman spectroscopy (SERS).³⁶ A similar SERS peak at 232 cm⁻¹ has been observed after treatment of *E. coli* with synthesized Ag NPs in our laboratory (data not shown), but the FE-SEM images (Figure 4, C and D) clearly show that the toxic effect of Ag-SiO₂ NPs results from, damage to the cell surface of *E. coli*.

In the presence of 10 µg/mL of SiO₂-Ag NPs, growth of both *E. coli* ATCC 25922 and *E. coli* O157:H7 was inhibited, and at 100 µg/mL, the bacteria did not grow even after 24 hours. At an Ag-SiO₂ NPs concentration of 100 µg/mL, 74% of the general *E. coli* and 64% of *E. coli* O157H7 were killed. However, at an Ag-c NP concentration of 8.5 µg/mL, 71% of the general *E. coli* ATCC 25922 were killed and 60% of *E. coli* O157:H7.

Furthermore, the broad spectrum of antibacterial properties of Ag-SiO₂ and Ag-c NPs was shown with both gram-negative and gram-positive bacteria. MIC values show that 125 µg/mL Ag-SiO₂ and 34 µg/mL Ag-c were sufficient to inhibit gram-negative bacteria [*E. coli* ATCC 25922, *E. coli* O157:H7, *Pseudomonas aeruginosa* ATCC 27853, *Salmonella enterica* ATCC 19585 (42.5 µg/mL; Ag-c NPs)], whereas 150 µg/mL Ag-SiO₂ and 42.5 µg/mL Ag-c were required to inhibit the gram-positive bacterium (*Bacillus cereus*). This difference could be due to the different bacterial concentrations as well as type of strain used.

In conclusion, Ag-SiO₂ and Ag-c NPs prepared by the cost-effective reduction method described here show great promise as antimicrobial agents against both gram-negative and gram-positive bacteria. Applications of these NPs based on our findings may lead to valuable discoveries in various fields such as improving water quality, medical devices, and antimicrobial systems.

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Figure 1. TEM images (A–D) of Ag-SiO₂ NPs and (E) Ag colloids NPs. (F–H) Size distribution graphs of (F) SiO₂ NPs (mean size = 73.53 nm), (G) Ag NPs linked with SiO₂ (mean size = 6.6 nm), and (H) Ag-c NPs (mean size = 3.5 nm).

Figure 2.

UV-visible spectra of (A) aqueous suspension of Ag-SiO₂ NPs at 1000, 100, 10, 1, and 0.1 µg/mL (top to bottom) and (B) aqueous solution of Ag-c NPs at 85, 42.5, 8.5, 0.85, 8.5×10^{-2} , and 8.5×10^{-3} µg/mL (top to bottom). (C, D) Antibacterial effect in culture tube after 24 hours' incubation of (C) Ag-SiO₂ NPs (lefthand tube contains 100 µg/mL Ag-SiO₂ NPs and *E. coli*, and righthand tube contains only *E. coli* control); (D) Ag-c NPs (lefthand tube contains 42.5 µg/mL Ag-c NPs with *E. coli*, and righthand tube contains only *E. coli* control). (E, F) Growth test of *E. coli* on agar plates. (E) Lefthand plate contains Ag-SiO₂ NPs + *E. coli*, and righthand plate contains only *E. coli* control, which contains $\sim 1.78 \times 10^6$ cfu of *E. coli*. (F) Lefthand plate contains Ag-c NPs + *E. coli*, and righthand plate contains only *E. coli* control, which contains $\sim 1.28 \times 10^6$ cfu of *E. coli*.

Figure 3.

Growth curve of *E. coli* (EC) ATCC 25922 (A) in presence of Ag-c NPs at a concentration of 0.85 (dark blue), 8.5 (pink), and 42.5 $\mu\text{g/mL}$ (red) with their positive controls (bacteria only) light blue, yellow, and violet, respectively, and negative control Ag-c NPs only (green line); (B) in presence of Ag-SiO₂ NPs at a concentration of 100 (pink) and 10 (violet) $\mu\text{g/mL}$, with bacteria only (green and red) and Ag-SiO₂ NPs only (dark blue and light blue), respectively. (C, D) Growth curve for *E. coli* O157:H7 (C) in presence of Ag-c NPs at concentration of 42.5 $\mu\text{g/mL}$ (pink), bacteria only (yellow), and NPs only (blue); (D) in presence of Ag-SiO₂ NPs at concentration of 100 $\mu\text{g/mL}$ (green), bacteria only (red), and NPs only (light blue).

Figure 4.

Colonies count of *E. coli* ATCC 25922 expressed as a percentage of the number of colonies grown on silver-free LB agar plates. **(A)** Ag-SiO₂ NPs at 0.1, 1, 10, and 100 μg/mL; **(B)** colloidal Ag NPs at 0.085, 0.85, 8.5, and 42.5 μg/mL. **(C, D)** FE-SEM images of **(C)** damaged *E. coli* ATCC 25922 and Ag-SiO₂ NPs complex; **(D)** damaged cell surface of single *E. coli* bacterium in presence of Ag-SiO₂ NPs.

Figure 5.

Fluorescent microscopy images of live and dead bacterial cells in presence of silver NPs, using green and red UV-visible filters, respectively. (A, B) 100 µg/mL Ag-SiO₂ NPs + *E. coli* ATCC 25922; (C, D) 8.5 µg/mL Ag colloid NPs + *E. coli* ATCC 25922; (E, F) control having only *E. coli* ATCC 25922; (G, H) 100 µg/mL Ag-SiO₂ NPs + *E. coli* O157:H7; (I, J) 8.5 µg/mL Ag colloid NPs + *E. coli* O157:H7; (K, L) control containing only *E. coli* O157:H7.

Figure 6.

Bar graph of live and dead (A) *E. coli* ATCC 25922, (B) *E. coli* O157:H7 in the presence and absence of Ag-c NPs, where bacterial cells counts are expressed as a function of percentage per milliliter.

Table 1Minimum inhibitory concentrations for Ag-SiO₂ and Ag-c NPs against five different bacterial strains

Bacteria	Ag-SiO ₂ NPs (μg/mL)	Ag-c NPs (μg/mL)
<i>E. coli</i> ATCC 25922	125	34
<i>E. coli</i> O157:H7	125	34
<i>Pseudomonas aeruginosa</i> ATCC 27853	125	34
<i>Salmonella enterica</i> ATCC 19585	125	42.5
<i>Bacillus cereus</i>	150	42.5