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Research Article

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Green-synthesized Silver Nanoparticles from *Cymbopogon citratus*: Synergistic Antibacterial Effects and Food Safety Potential

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Abstract

This study investigates the antibacterial properties and stability of green-synthesized silver nanoparticles (AgNPs) using *Cymbopogon citratus* extract, with a focus on their synergistic effects with conventional antibiotics (Abs) and potential applications in food safety. The AgNPs were evaluated against nine bacterial strains, both alone and in combination with standard Abs (ampicillin (Amp), chloramphenicol (Chl), kanamycin (Km), and penicillin (Pen)) using the agar well diffusion method. Combining AgNPs with Abs significantly enhanced antibacterial activity against several strains, notably *Escherichia coli* with Km (26.90%), *Klebsiella pneumoniae* with ampicillin (21.66%), and *Staphylococcus aureus* with Chl (46.93%). However, certain combinations, such as Pen with *Bacillus subtilis* and *K. pneumoniae*, showed reduced effectiveness. Stability studies revealed that AgNPs stored in distilled water (DW) at 4 °C over 40 days exhibited a gradual decrease in absorbance (from 0.221 - 0.142 a.u.) and a slight wavelength shift (423 nm - 420 nm), indicating minor changes in their optical properties. The results highlight the potential of AgNPs as antimicrobial agents capable of enhancing Ab efficacy, with promising applications in food preservation and packaging to combat foodborne pathogens and extend shelf life.

Keywords

Antibacterial activity, Antibiotic synergy, Food safety, Green synthesis, Nanotechnology, Silver nanoparticles, Stability

Introduction

In recent years, the advent of nanotechnology has significantly transformed various scientific fields, including medicine, food science, and materials science [1, 2]. Among the numerous nanomaterials developed, AgNPs have garnered considerable attention due to their remarkable physicochemical properties and broad-spectrum biological activities [3, 4]. AgNPs are particularly noted for their potent antibacterial properties, making them a promising candidate for combating multidrug-resistant bacterial strains, offering promising applications in food safety and preservation [5, 6]. This has led to an increasing interest in developing environmentally friendly and sustainable methods for synthesizing AgNPs, often referred to as "green synthesis" approaches [7, 8]. One such method involves the use of plant extracts as reducing and stabilizing agents, a process that not only minimizes the use of hazardous chemicals but also offers a cost-effective and scalable alternative to conventional synthesis methods by incorporating bioactive phytochemicals from plants, enhancing AgNPs' antibacterial efficacy [9, 10].

Among the various plants explored for green synthesis, *C. citratus*, commonly known as lemongrass, stands out due to its rich phytochemical profile [11]. *C.*

citratus is widely known for its essential oil, which contains bioactive compounds such as citral, flavonoids, phenolic acids, and alkaloids [12]. These compounds not only facilitate the reduction of silver (Ag^+) ions to AgNPs but also impart additional bioactive properties to the AgNPs, thereby enhancing their antibacterial efficacy [13]. The use of *C. citratus* extract in the synthesis of AgNPs offers a dual advantage: it provides a green synthesis route and enhances the biological activity of the resulting AgNPs [12, 14-16].

The antibacterial properties of AgNPs synthesized using *C. citratus* extract have been demonstrated in several studies, showing effectiveness against a broad spectrum of bacterial pathogens, including both Gram-positive and Gram-negative strains [12, 14-16]. However, the specific mechanisms underlying their antibacterial action are still under investigation. Generally, the antibacterial effect of AgNPs is attributed to several mechanisms, including the generation of reactive oxygen species (ROS), disruption of bacterial cell membranes, and interference with cellular processes such as DNA replication [17-19]. Moreover, AgNPs have been reported to induce a synergistic antibacterial effect when used in combination with conventional Abs, potentially restoring the efficacy of Abs against resistant bacterial strains [20, 21].

In addition to their antibacterial properties, the stability of AgNPs is a crucial factor that determines their practical applications in food technology [22, 23]. AgNPs tend to aggregate over time, which can lead to a loss of their unique properties and a reduction in their effectiveness [24]. The stability of AgNPs is influenced by several factors, including the size, shape, and surface charge, as well as the nature of the capping agents used during synthesis [25, 26]. In the case of AgNPs synthesized using *C. citratus* extract, the phytochemicals present in the extract act as capping agents, providing steric and electrostatic stabilization to the AgNPs. This not only prevents aggregation but also contributes to the long-term stability of the AgNPs in various environmental conditions to ensure consistent performance in food packaging and antimicrobial applications [27].

AgNPs possess potent antibacterial properties that play a significant role in enhancing food safety by preventing the growth of harmful microorganisms. When incorporated into packaging materials such as plastic films, coatings, or edible wraps, AgNPs create an active barrier against bacteria, fungi, and other pathogens, reducing spoilage and extending the shelf life of food products. This not only helps maintain the quality and safety of food but also decreases the need for synthetic preservatives, which are often associated with health concerns. By minimizing bacterial contamination, AgNPs-infused packaging materials contribute to a safer food supply and reduce food waste, supporting global food security efforts.

Given the potential of AgNPs in combating bacterial infections, particularly in the face of rising Ab resistance, it is imperative to thoroughly investigate their synergistic effects with Abs, and stability over time [28, 29]. This study aims to explore the antibacterial activity of green-synthesized AgNPs, particularly those mediated by plant extracts like *C. citratus*, offer a promising solution due to their potent antibacterial activity, potential to work synergistically with existing Abs, and environmental compatibility. This study builds on previous research by not only assessing the antibacterial properties of *C. citratus*-mediated AgNPs but also examining their stability, a critical factor for their practical application.

Materials and Method

Materials

Standard Abs (Amp, Chl, Km, and Pen), and 0.22 µm PVDF syringe filters were purchased from HiMedia laboratories Pvt. Ltd. (India). DW (pH was in the range of 6.6 to 7.4) was used for the work. The pH of solutions was adjusted by using 1 M sodium hydroxide and 1 N hydrochloric acid, accordingly wherever required. Preparation of stock solutions and necessary dilutions were made using DW. Non-ionic detergent was used to wash the glassware, later rinsed with DW several times, and then dried in hot air oven before use. Figure 1 presents the schematic representation of the reported work.

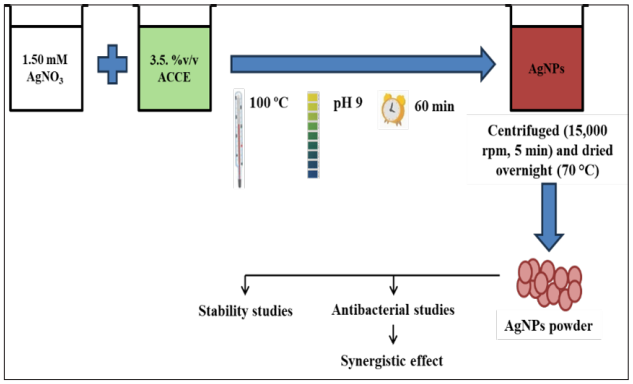

Figure 1: Schematic representation of the reported work.

Antibacterial studies

Bacterial strains and culture

A total of 9 bacterial species were used such as *Acinetobacter baumannii*, *B. subtilis*, *Enterococcus faecalis*, *E. coli*, *K. pneumoniae*, *Micrococcus luteus*, *Proteus vulgaris*, *Pseudomonas aeruginosa*, and *S. aureus*. The cultures were provided by Dr. Venkataramana Kandi (Assistant Professor), Department of Microbiology, Prathima Institute of Medical Sciences, Karimnagar (Telangana, India). The cultures obtained were regularly sub-cultured in nutrient agar plates and upon requirement, pre-inoculum was prepared in nutrient broth.

Stock solutions

AgNPs stock solution was prepared by adding 1 mg of AgNPs in 1 ml of DW. Furthermore, the solution was sonicated (20% amplitude, 10 min, pulse on/off 5 sec) for uniform distribution of AgNPs in the solution. The AgNPs were sonicated under same conditions before use. Standard Abs (Amp, Chl, Km, and Pen) were prepared by dissolving 1 mg of Ab in 1 ml of DW, individually. Combination of AgNPs and standard Abs solutions were prepared by mixing 1 mg of AgNPs and Abs in 1 ml of water, individually. Later, the combination solutions were incubated for 24 h at 4 °C for proper mixing. All stock solutions are prepared freshly and used. Ab stock solutions were filtered through PVDF filters.

Synergistic effect - agar well diffusion assay

The agar well diffusion assay is a widely used technique in microbiology to evaluate the antimicrobial properties of various substances, including AgNPs. In this method, a test bacterium (50 µl of fresh pre-inoculum) was uniformly spread across the surface of an agar plate, and wells are then created in the agar medium using sterile well borer (diameter 6 mm). AgNPs (10 µl) and standard Abs (10 µl) were then introduced into the wells and labelled accordingly. Further, the agar plates were incubated in static incubator at 37 °C for 24 h, inversely. During incubation, they diffuse through the agar and interact with the surrounding bacterial cells. The effectiveness of the AgNPs and standard Abs was determined by measuring the zone of inhibition (ZOI), a clear area around the well where bacterial growth has been prevented [30].

The antibacterial potential of AgNPs was also assessed in combination with standard Abs such as Amp, Chl, Km, and Pen by loading the wells with both AgNPs and Abs (10 µl) stock solutions. The ZOI was measured and recorded accordingly. Synergistic activity was calculated using equation 1 [20, 21], which provides the percentage fold increase in the ZOI. Additionally, the activity index of AgNPs relative to the standard Abs was determined using equation 2 [20, 21].

$$\text{Fold Increase in ZOI (\%)} = \left(\frac{\text{B-A}}{\text{A}}\right) \times 100 \quad (1)$$

Where "A" and "B" are ZOI of standard Ab alone and in combination with AgNPs, respectively.

$$\text{Activity Index} = \frac{\text{ZOI of NPs}}{\text{ZOI of antibiotic}} \quad (2)$$

Stability studies

This study aims to explore the stability of AgNPs in DW at 4 °C by examining changes in optical properties over time. 10 µl of AgNPs was mixed with 990 µl of DW followed by sonication for uniform distribution and stored at 4 °C. Ultraviolet-visible spectrophotometer (UV-Vis spec) was recorded in the range of 300 to 700 nm every 10 days (i.e., Day 0, 10, 20, 30, and 40). The findings will provide insights into the suitability of low-temperature storage for maintaining the stability and functionality of AgNPs in aqueous environments.

Statistical analysis

All experiments were conducted in triplicate. Statistical significance (p-value) was assessed using the student's t-test in MS Office 2021, while Origin 2024b was employed to graphically represent the results.

Results and Discussion

Antibacterial studies

Antibacterial studies on AgNPs are of significant importance due to their potent and broad-spectrum antibacterial properties, which have shown promise in addressing the growing global challenge of Abs resistance [31, 32]. AgNPs possess unique physicochemical characteristics, such as a high surface area-to-volume ratio and the ability to generate ROS, which enable them to effectively disrupt bacterial cell membranes, interfere with cellular processes, and inhibit biofilm formation [33, 34]. Unlike conventional Abs, which often target specific bacterial mechanisms, AgNPs exhibit multiple modes of action, reducing the likelihood of resistance development [35]. These properties make AgNPs a valuable tool in the development of new antibacterial therapies, particularly in the context of multidrug-resistant pathogens, where they can be used alone or in combination with existing Abs to enhance efficacy and restore the effectiveness of traditional treatments.

Synergistic effect

This study investigated the synergistic effects of AgNPs when used alongside standard Abs, such as Amp, Chl, Km, and Pen, against various bacterial strains using the agar well diffusion assay. The Abs tested were Amp, Chl, Km, and Pen, in combination with AgNPs, each at a concentration of 10 µg/well. Table 1 presents the ZOI (in mm) for standard Abs alone and in combination with AgNPs, enhanced ZOI in percentage, and activity index at 10 µg/well concentration against test bacteria.

The combination of Abs with AgNPs generally enhanced antibacterial activity, though the effect varied by Ab and bacterial strain. Against *A. baumannii* (Figure 2), all Abs showed increased activity, with Amp exhibiting the highest enhancement (6.79%). For *B. subtilis* (Figure 3), Pen showed the most significant increase (14.13%), while Km's activity decreased by 6.11%. Against *E. faecalis* (Figure 4), Amp and Km showed increased activity (3.84% and 13.48%, respectively), whereas Chl and Pen experienced slight reductions. For *E. coli* (Figure 5), Km displayed the highest enhancement (26.90%), while Amp showed no change and Pen slightly decreased. Against *K. pneumoniae* (Figure 6), Amp had the most notable improvement (21.66%), while Km and Pen showed slight reductions. For *M. luteus* (Figure 7), Chl and Km showed mild enhancements (~5%), while Pen remained virtually unchanged. Against *P. vulgaris* (Figure 8), Amp and Pen exhibited increased activity, while Chl and Km showed reduced effectiveness. For *P. aeruginosa* (Figure 9), Amp and Km showed significant enhancement (11.83% and 18.50%, respectively), while Chl slightly decreased. Against *S. aureus* (Figure 10), Chl displayed a substantial enhancement (46.93%), while Amp and Pen showed slight reductions.

Overall, the combination of standard Abs with AgNPs generally resulted in enhanced antibacterial activity, as reflected by increased ZOIs and higher activity indices in several cases. However, the effectiveness varied depending on the specific Ab-bacteria pairing. Notably, *E. coli* showed significant improvement with Km, while *S. aureus* responded particularly well to Chl. Conversely, some combinations, particularly involving Pen, did not show significant improvement or even resulted in reduced effectiveness.

Possible antibacterial mechanism based on literature

The antibacterial mechanism of AgNPs is multifaceted, involving several key processes that disrupt bacterial survival and proliferation. These mechanisms, which occur at both the extracellular and intracellular levels, are critical for understanding how AgNPs exert their antibacterial effects (Figure 11) [36-39].

Table 1: ZOI (in mm) of standard Abs alone and in combination with AgNPs, enhanced ZOI in percentage, and activity index at 10 µg/well concentration against test bacteria. a indicates $p > 0.05$, b indicates $p > 0.005$, and c indicates $p > 0.0005$.

Bacteria	Antibiotics	ZOI (in mm)		Enhanced ZOI	Activity index
	(10 µg/well)	Ab	Ab + NPs	(%)	-
A. baumannii	Amp	14.96 ± 0.37	15.97 ± 0.24[b]	6.79 ± 1.47	0.936 ± 0.039
	Chl	16.14 ± 0.11	17.12 ± 0.09[b]	6.10 ± 1.13	0.867 ± 0.023
	Km	15.89 ± 0.34	16.86 ± 0.25[b]	6.13 ± 2.16	0.881 ± 0.011
	Pen	18.20 ± 0.64	18.93 ± 0.54[a]	4.05 ± 0.70	0.769 ± 0.029
B. subtilis	Amp	9.77 ± 0.34	9.91 ± 0.38[a]	1.46 ± 0.58	0.674 ± 0.048
	Chl	13.18 ± 0.27	13.52 ± 0.27	2.56 ± 1.24	0.501 ± 0.062
	Km	10.07 ± 0.29	9.46 ± 0.44	-6.11 ± 2.29	0.655 ± 0.073
	Pen	13.70 ± 0.41	15.62 ± 0.16[c]	14.13 ± 4.50	0.481 ± 0.052
E. faecalis	Amp	9.88 ± 0.28	10.26 ± 0.35[b]	3.84 ± 1.03	1.172 ± 0.026
	Chl	18.23 ± 0.53	17.44 ± 0.37	-4.35 ± 0.78	0.635 ± 0.009
	Km	9.36 ± 0.29	10.62 ± 0.32[c]	13.48 ± 2.14	1.237 ± 0.024
	Pen	20.62 ± 0.27	20.32 ± 0.20	-1.47 ± 0.39	0.562 ± 0.018
E. coli	Amp	6.00 ± 0.00	6.00 ± 0.00	-	-
	Chl	6.66 ± 0.59	7.45 ± 0.55[c]	11.91 ± 1.81	0.999 ± 0.059
	Km	6.64 ± 0.29	8.43 ± 0.27[c]	26.90 ± 2.41	1.005 ± 0.139
	Pen	12.09 ± 0.59	11.60 ± 0.51	-4.09 ± 0.86	0.552 ± 0.069
K. pneumoniae	Amp	12.68 ± 0.30	15.43 ± 0.60[c]	21.66 ± 3.39	1.177 ± 0.041
	Chl	16.38 ± 0.30	16.51 ± 0.31	0.77 ± 0.63	0.911 ± 0.013
	Km	16.81 ± 0.41	16.41 ± 0.38	-2.40 ± 0.73	0.888 ± 0.008
	Pen	19.22 ± 0.12	18.65 ± 0.18	-2.98 ± 0.42	0.776 ± 0.016
M. luteus	Amp	13.45 ± 0.30	13.85 ± 0.22	2.99 ± 1.75	0.897 ± 0.035
	Chl	15.21 ± 0.21	16.01 ± 0.18[a]	5.29 ± 1.14	0.793 ± 0.020
	Km	16.27 ± 0.44	17.12 ± 0.36[b]	5.22 ± 1.25	0.742 ± 0.038
	Pen	17.75 ± 0.52	17.75 ± 0.47	-0.01 ± 1.07	0.680 ± 0.007
P. vulgaris	Amp	6.14 ± 0.24	6.69 ± 0.21[a]	9.04 ± 1.11	1.175 ± 0.038
	Chl	16.75 ± 0.10	16.48 ± 0.31	-1.59 ± 1.85	0.431 ± 0.020
	Km	11.12 ± 0.33	9.69 ± 0.54	-12.85 ± 2.40	0.648 ± 0.009
	Pen	17.41 ± 0.24	18.20 ± 0.05[a]	4.55 ± 1.39	0.414 ± 0.013
P. aeruginosa	Amp	11.47 ± 0.69	12.82 ± 0.60[b]	11.83 ± 1.71	1.368 ± 0.085
	Chl	16.34 ± 0.53	15.82 ± 0.38	-3.18 ± 1.10	0.959 ± 0.014
	Km	14.17 ± 0.37	16.79 ± 0.59[c]	18.50 ± 2.06	1.105 ± 0.018
	Pen	19.74 ± 0.21	19.81 ± 0.16	0.34 ± 0.51	0.793 ± 0.016
S. aureus	Amp	14.89 ± 0.45	14.50 ± 0.25	-2.64 ± 1.56	0.991 ± 0.024
	Chl	10.52 ± 0.47	15.44 ± 0.21[c]	46.93 ± 5.06	1.405 ± 0.059
	Km	14.78 ± 0.45	15.04 ± 0.52	1.75 ± 0.98	0.999 ± 0.032
	Pen	15.88 ± 0.64	15.82 ± 0.69	-0.39 ± 0.35	0.930 ± 0.027

AgNPs exhibit potent antibacterial activity through multiple mechanisms. They attach to bacterial cell membranes via electrostatic interactions, increasing membrane permeability and causing structural damage, including pore formation and membrane thinning, which leads to leakage of vital cellular contents and cell death [40-42]. AgNPs also catalyze the generation of ROS like superoxide anions and hydroxyl radicals, causing oxidative stress that damages lipids, proteins, and DNA, ultimately leading to cell death [43-45]. By binding on bacterial proteins, particularly those with thiol groups, AgNPs inactivate essential enzymes, disrupting metabolism and energy production [46, 47]. They also interfere with DNA replication and transcription by binding to bacterial DNA, impeding cell division and protein synthesis [28, 48, 49]. AgNPs effectively disrupt biofilms by penetrating the matrix and delivering concentrated Ag^+ ions, making bacteria more susceptible to Abs [50-52]. The continuous release of Ag^+ ions ensures prolonged antibacterial activity by interacting with proteins,

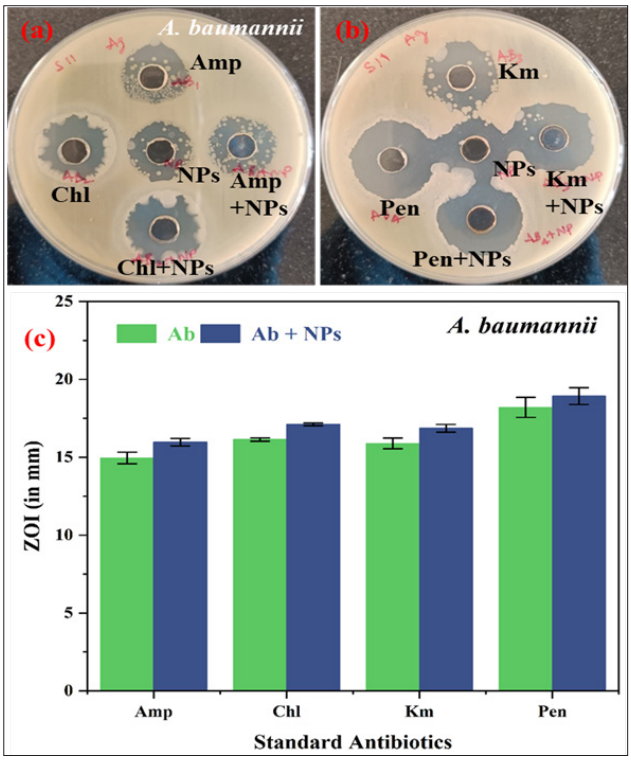

Figure 2: Against *A. baumannii*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

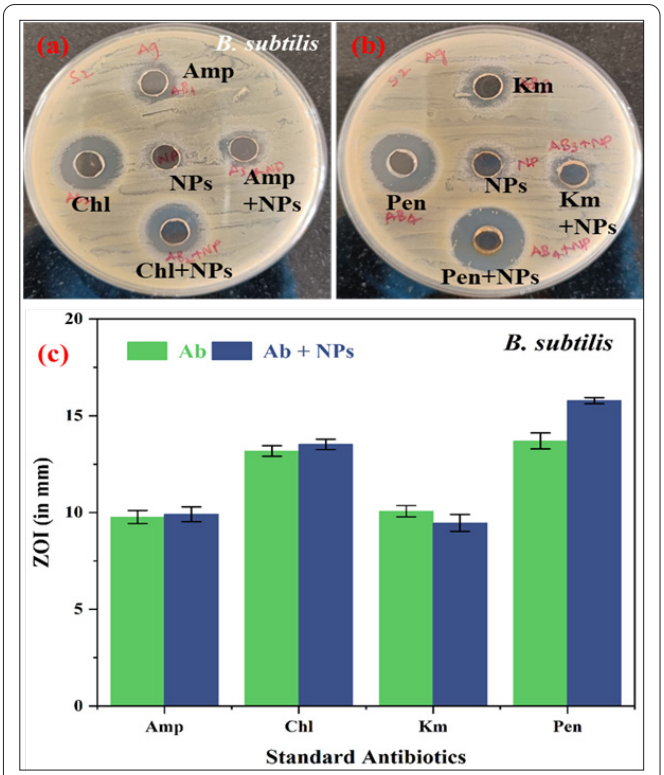

Figure 3: Against *B. subtilis*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in

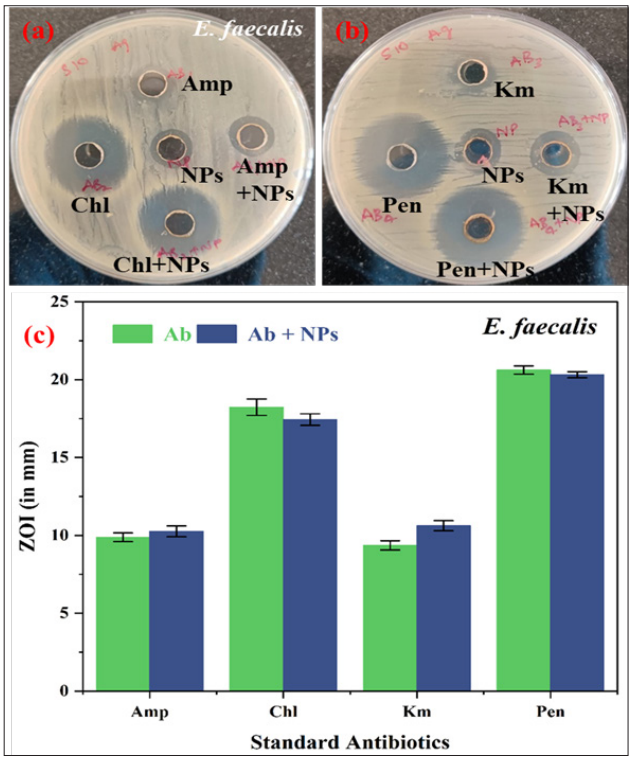

Figure 4: Against *E. faecalis*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

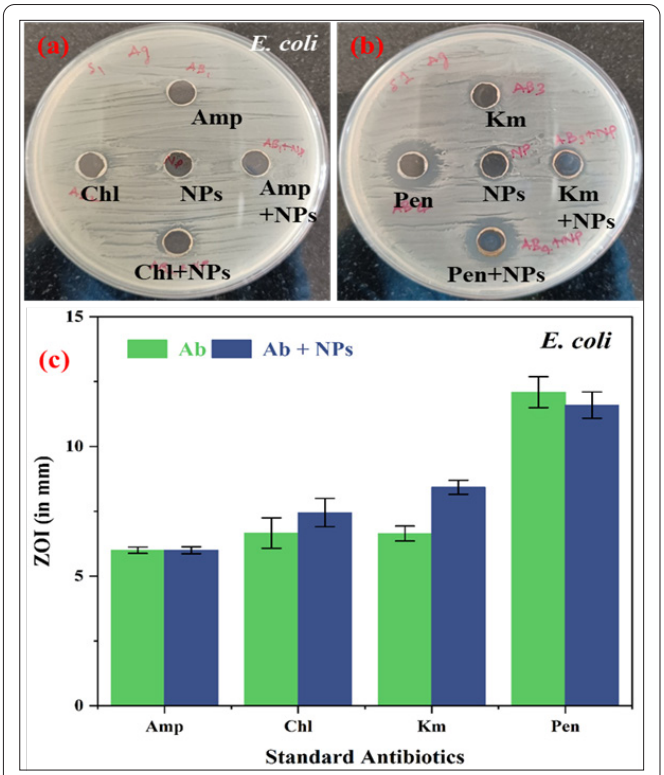

Figure 5: Against *E. coli*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

membranes, and DNA [53, 54]. Additionally, AgNPs enhance the effectiveness of Abs by weakening bacterial defenses, such as efflux pumps and Ab-degrading enzymes, making them particularly effective against resistant strains [55].

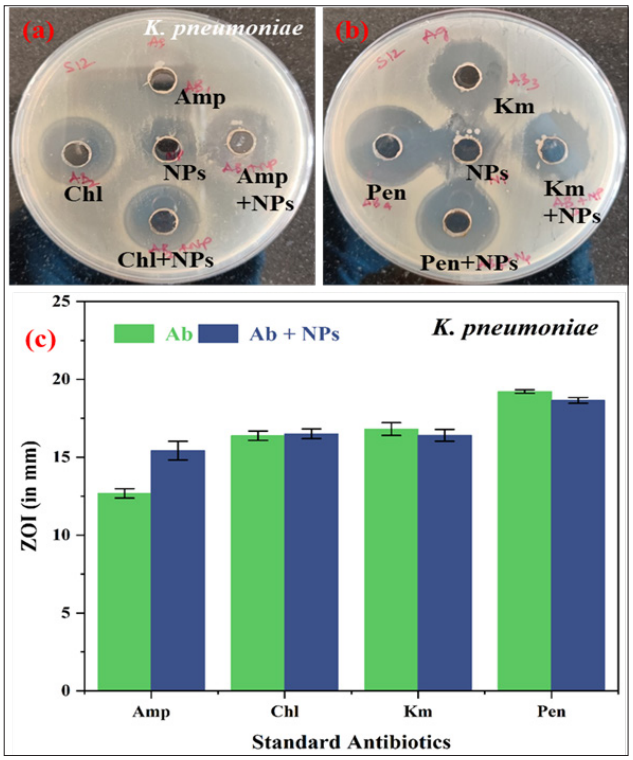

Figure 6: Against *K. pnemoniae*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

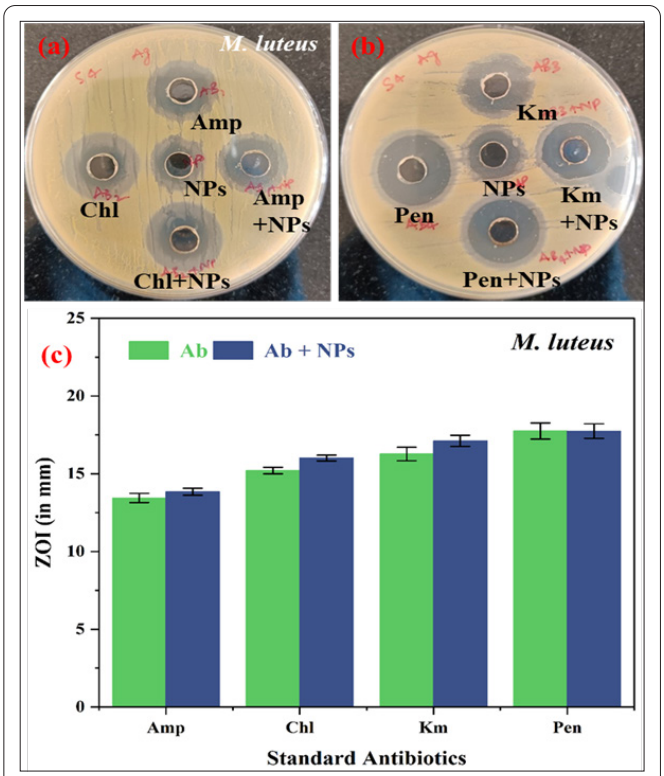

Figure 7: Against *M. luteus*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard antib Abs iotics alone and in combination with AgNPs.

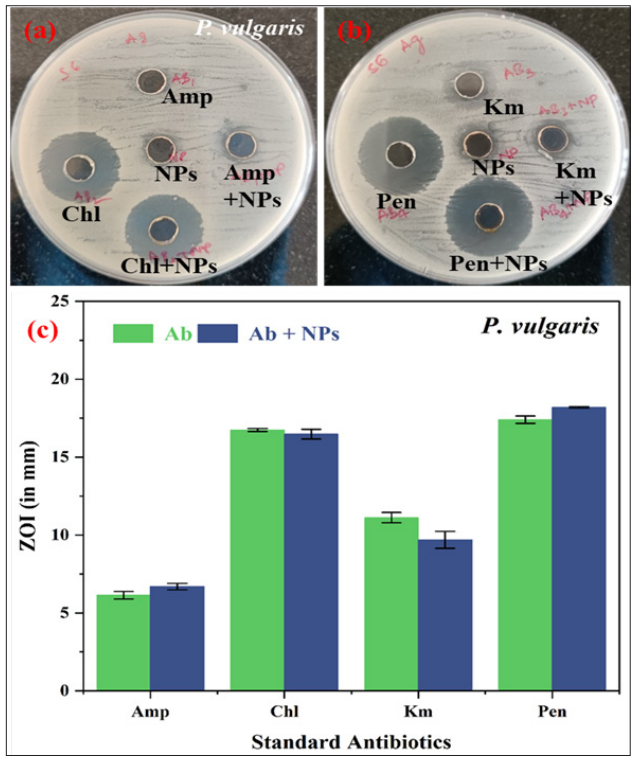

Figure 8: Against *P. vulgaris*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

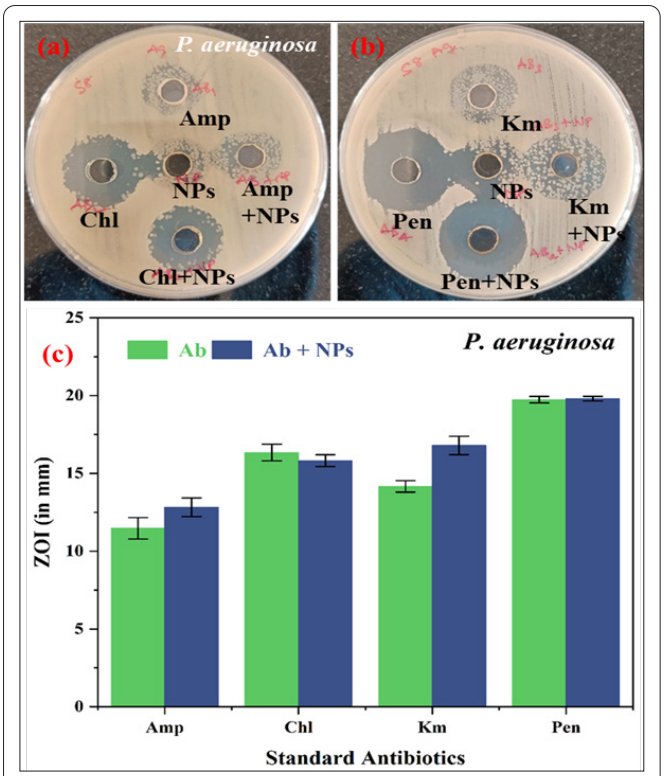

Figure 9: Against *P. aeruginosa*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

In summary, the antibacterial mechanisms of AgNPs are diverse and synergistic, making them powerful antibacterial agents with the potential to combat a wide range of bacterial pathogens, including those resistant to conventional Abs.

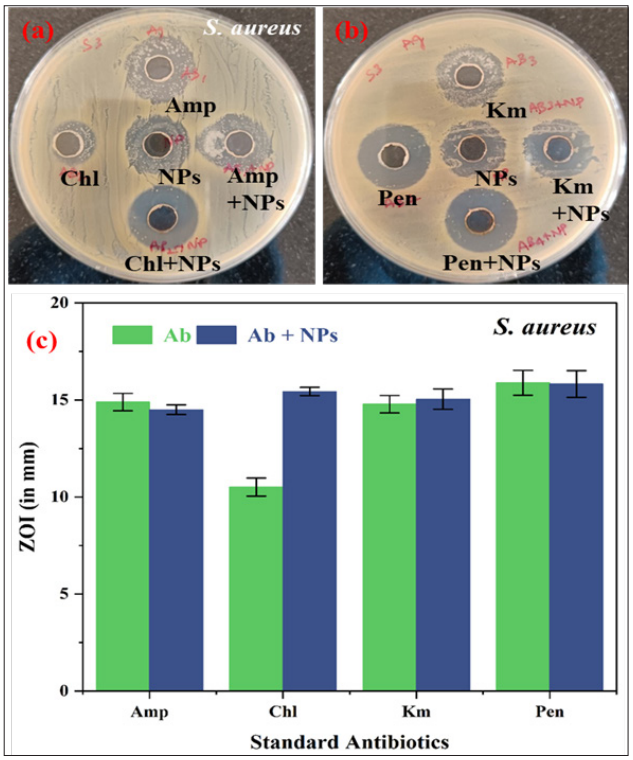

Figure 10: Against *S. aurues*. Agar plates in presence of **(a)** Amp and Chl alone and in combination with AgNPs, **(b)** Km and Pen alone and in combination with AgNPs, and **(c)** Bar graph showing ZOI (in mm) of standard Abs alone and in combination with AgNPs.

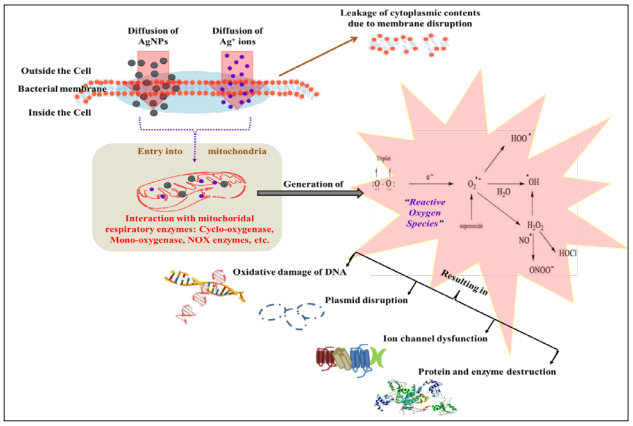

Figure 11: Schematic representation of possible antibacterial mechanism in presence of AgNPs based on literature [36-39].

By attacking multiple targets within bacterial cells, AgNPs minimize the chances of resistance development and provide a versatile approach to enhancing the efficacy of existing antibacterial therapies.

Stability studies

DW is commonly used as a medium for suspending AgNPs due to its purity and absence of ions or contaminants that could influence the behavior of the AgNPs [56, 57]. However, even in DW, various factors such as temperature, pH, and time can impact the stability of AgNPs. Temperature is a critical factor influencing the stability of AgNPs. At lower temperatures, such as 4 ˚C, the kinetic energy of the AgNPs decreases, which can reduce the rate of agglomeration and oxidation processes [58, 59]. This suggests that storing AgNPs at 4 ˚C might enhance their stability by minimizing these adverse effects. Understanding how these factors affect AgNPs' stability is essential for optimizing their storage conditions and ensuring their reliability in applications.

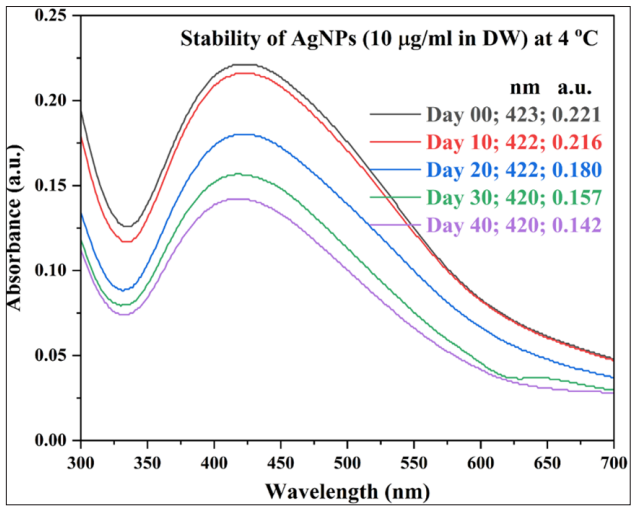

Figure 12: Stability studies of AgNPs at 10 µg/ml in DW (pH was in the range of 6.6 - 7.4) at 4 ˚C using UV-Vis spec.

The stability of AgNPs in DW at 4 ˚C was monitored over a 40-day period (Figure 12). At day 0, the AgNPs exhibited a wavelength of 423 nm with an absorbance of 0.221 a.u. After 10 days, the wavelength slightly decreased to 422 nm, and the absorbance dropped marginally to 0.216 a.u. By day 20, the wavelength remained at 422 nm, but the absorbance further decreased to 0.180 a.u. On day 30, a more noticeable change occurred, with the wavelength reducing to 420 nm and absorbance dropping to 0.157 a.u. Finally, on day 40, the wavelength remained at 420 nm, while the absorbance decreased to 0.142 a.u. These observations suggest a gradual reduction in absorbance and a slight shift in wavelength over time, indicating marginal changes in the optical properties of AgNPs when stored at 4 ˚C in DW.

For instance, *Citrus aurantifolia* fruit peel extract has been shown to produce stable AgNPs, maintaining stability for up to 10 months [60]. Similarly, *Ziziphus spina-christi* seed extract resulted in AgNPs with high stability over 8 months, attributed to the capping effect of biomolecules [61]. AgNPs stored in the dark at 5 ˚C exhibited the best long-term stability, maintaining their size and preventing agglomeration for over 6 months [62]. AgNPs synthesized using bamboo hemicellulose, remained stable at 4 ˚C for 160 days [63]. The use of specific plant extracts, like those from *Rosa damascena*, resulted in NPs with an average size of 20 nm, which were stable for at least three months [64].

The stability of AgNPs in different environments is crucial for their effective application and long-term storage. The stability of AgNPs refers to their ability to maintain size, shape, and dispersion over time without agglomeration or significant changes in their properties. However, the specific behavior of AgNPs in DW needs to be thoroughly investigated to determine the optimal storage temperature.

Conclusion

The study demonstrates that AgNPs exhibit variable antibacterial activity against different bacterial strains, with some strains responding more effectively than others. In most cases, standard Abs, especially Pen and Chl, display stronger antibacterial effects compared to AgNPs. However, when combined with AgNPs, certain Abs, such as Amp, Chl, and Km, showed enhanced antibacterial activity against specific bacteria, although the effects were not universally positive, with some combinations resulting in reduced effectiveness. Additionally, stability studies of AgNPs stored in DW at 4 °C, over 40 days revealed a gradual decrease in absorbance and a slight shift in wavelength, indicating minor changes in their optical properties, underscoring the importance of optimizing storage conditions for maintaining their stability.

Future Prospects

The antibacterial properties of AgNPs are exceptionally beneficial in the realm of food safety, where contamination by bacteria, fungi, and other pathogens poses a significant risk to both health and food preservation. AgNPs can be integrated into food packaging materials, such as plastic films, coatings, or edible wraps, to create an active barrier against bacterial growth. This incorporation helps to inhibit the proliferation of harmful microorganisms that can lead to food spoilage, thus maintaining the quality and safety of food products for extended periods.

In addition to packaging, AgNPs can also be used in food preservation processes, where their antibacterial action helps to reduce or eliminate the need for synthetic preservatives, which are often linked to health concerns. By controlling bacterial growth, AgNPs not only extend the shelf life of food but also ensure that the food remains safe for consumption, reducing the risk of foodborne illnesses.

Furthermore, by enhancing food safety through the use of AgNPs, there is a direct positive impact on food security. Food security is fundamentally about ensuring that sufficient, safe, and nutritious food is available to meet the dietary needs of the population. By reducing spoilage and waste, AgNPs help maintain a stable and reliable food supply, which is particularly important in regions where food resources are scarce or where transportation and storage conditions are challenging. In this way, AgNPs contribute to a more efficient food system, helping to reduce food losses from farm to fork, and ensuring that more food reaches consumers in a safe and edible state. This ultimately supports global efforts to achieve food security, particularly in developing countries where food preservation is critical to sustaining local populations.

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Conflict of Interest

None.

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