Preliminary Progress of Green Synthesis and Characterization of Silver Nanoparticles Using *Allium cepa* Reducing Agent

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Abstract*– Antimicrobial resistance (AMR) represents a global health and economic crisis, with a particularly severe impact in developing regions such as Latin America, where access to effective antimicrobials is limited. At the same time, the agroindustry generates vast volumes of organic waste, such as onion peel (Allium cepa), which remains largely unvalorized. This study introduces a sustainable technological innovation: the green synthesis of silver nanoparticles (AgNPs) using Allium cepa extract as both a reducing and stabilizing agent. The AgNPs were characterized by UV-Vis (SPR at 425 nm) and FTIR, which indicate the formation of AgNPs capped by flavonoids and organosulfur compounds. Preliminary UV-Vis data suggest a narrow size distribution; however, morphological and crystallographic characterization (SEM/TEM, DLS, XRD) is required to confirm shape and monodispersity. Antimicrobial evaluation revealed inhibition zones of ~14 mm against E. coli and ~16 mm against S. aureus. Beyond the scientific findings, this work proposes an innovation model with entrepreneurial potential: (i) valorization of agroindustrial waste through circular economy, (ii) development of a high value-added product (AgNPs) with applications in active food packaging and antimicrobial coatings, and (iii) opportunities for the creation of technology-based enterprises (spin-offs) in onion-producing regions of Latin America. This approach demonstrates that green nanotechnology can serve as a driver of sustainable regional development, aligned with the innovation and entrepreneurship goals of the new millennium economy.

***Keywords* — Silver nanoparticles, green synthesis, Allium cepa, circular economy, technological entrepreneurship, sustainable regional development**

I. Introducción

The escalating crisis of antimicrobial resistance (AMR) represents a profound global threat, currently responsible for approximately 700,000 deaths annually, a figure projected to rise to 10 million by 2050 if left unchecked [1,2]. This challenge is further compounded by invasive fungal infections, which affect over 300 million people worldwide and result in more than 2 million deaths each year [3,4]. A significant driver of this mortality is the structural resilience of bacterial biofilms, responsible for approximately 60% of human infectious diseases and rendering conventional antibiotics largely ineffective [5,6]. In clinical settings, nosocomial infections caused by multidrug-resistant species such as *Staphylococcus aureus* exhibit alarmingly high mortality rates, often exceeding 40% [7,8]. The inability of standard pharmaceutical interventions to penetrate the extracellular matrix of these pathogens necessitates the development of innovative antimicrobial agents. Consequently, the integration of nanotechnology into medicine has become a critical frontier, as nanoscale materials possess unique physicochemical properties capable of overcoming prevalent microbial resistance mechanisms.

Addressing this crisis requires moving beyond traditional physical and chemical synthesis methods. Conventional techniques, such as chemical reduction, frequently involve toxic and volatile reagents like sodium borohydride or hydrazine that pose significant risks to human health and environmental integrity. Physical methods, including laser ablation and microwave irradiation, while effective, are often restricted by high energy consumption and the need for complex, costly equipment. In contrast, green synthesis or biosynthesis has emerged as a sustainable and cost-effective alternative that utilizes non-toxic, renewable reagents from diverse biological sources, ranging from terrestrial plants and marine algae to fermented substrates [9–17]. This eco-friendly approach leverages natural biomolecules as both a reducing and stabilizing agent, producing biocompatible nanoparticles that are safer for clinical applications and eliminate hazardous by-products.

Recent research has highlighted the potential of various plant sources in this field. Beyond onion, biogenic reduction has also been reported across a taxonomically diverse range of matrices, including Senna alata [18], Centaurea saligna [19], Lepidium sativum [20], Pentapetes phoenicea [21], Cinchona species [22], Satureja spp. [23], Withania coagulans [24], Citrus medica [25], and fungal biomass such as Phytophthora infestans [26], underscoring the broad applicability of this synthesis route. Focusing specifically on *Allium cepa*, Saxena et al. [27] utilized onion extract to successfully synthesize silver nanoparticles with effective antibacterial activity against pathogenic strains. Similarly, Yap et al. [28] applied water extracts of onion peel for the green synthesis of AgNPs, finding them useful as efficient catalysts. Chand et al. [29] further characterized AgNPs synthesized from neem, onion, and tomato extracts, concluding that these biogenic particles exhibit significant antimicrobial effects against S. aureus. Across these studies, nanoparticle formation and characterization have relied

on a consistent analytical framework: Ultraviolet-Visible (UV-Vis) spectroscopy to confirm formation via surface plasmon resonance, Fourier-Transform Infrared (FTIR) spectroscopy to identify functional groups, and X-ray diffraction (XRD) alongside scanning or transmission electron microscopy (SEM/TEM) to determine crystalline structure and morphology.

The applications of biogenic silver nanoparticles extend well beyond their direct antimicrobial role against multidrug-resistant pathogens. In agriculture, green-synthesized AgNP formulations have demonstrated potent antifungal activity against economically significant phytopathogens, including complete inhibition of fungi responsible for crop rot and blight, positioning them as candidates for next-generation, eco-friendly fungicides that reduce reliance on conventional agrochemicals [30]. Beyond crop protection, plant-derived AgNPs have also been incorporated into food packaging and preservation systems, where their antibacterial, antioxidant, and antifungal properties enable controlled silver release, extend shelf life, reduce microbial contamination, and, in some formulations, provide smart color-change indicators of spoilage [31]. In the biomedical field, onion-derived and other plant-mediated AgNPs have been explored for wound dressings and antimicrobial coatings, where sustained ion release and biocompatibility support infection control with lower cytotoxicity than chemically synthesized counterparts [5,6]. More broadly, plant-based AgNPs have shown multifunctional applications spanning environmental remediation, industrial catalysis, drug delivery, and wound healing, underscoring their translational versatility across sectors [32]. Collectively, these findings position *Allium cepa*-derived AgNPs not merely as an academic alternative to chemical synthesis, but as a versatile platform with relevance across medicine, agriculture, food science, and environmental technology.

The justification for utilizing *Allium cepa* as a reducing agent in medical applications lies in its rich phytochemical profile. Onion extract contains secondary metabolites — flavonoids like quercetin, phenolic compounds, and organic acids — that act as highly efficient natural bioreductants, consistent with reports on other *Allium* species [9]. These biomolecules facilitate the conversion of silver ions (Ag^{+}) to metallic silver nanoparticles (Ag^{0}) while also acting as capping agents that prevent agglomeration and confer long-term colloidal stability. These biogenic nanoparticles exhibit a high surface-area-to-volume ratio, enabling effective interaction with bacterial cell membranes and disruption of vital cellular machinery through reactive oxygen species generation. Compared with chemically synthesized counterparts, *Allium cepa*-derived AgNPs offer superior biocompatibility and significantly lower cytotoxicity, ensuring greater safety for human health [5,6]. Using this widely available bioresource also aligns with sustainable principles by repurposing agricultural residues into high-value medical materials.

Despite these scientific advances, the translation of green nanotechnology from the laboratory to commercially viable and socially impactful applications face significant barriers, particularly in developing countries. In Latin America, onion production exceeds 2.5 million tons annually, generating thousands of tons of waste (peels and leaves) that are currently discarded without valorization. This residual biomass represents an underutilized raw material with high potential for the synthesis of value-added nanomaterials. Therefore, this study not only addresses the urgent need for new antimicrobial agents but also proposes a sustainable innovation model that integrates circular economy (waste as input), technology transfer (reproducible and scalable protocol), and technology-based entrepreneurship (potential for the creation of spin-offs or cooperatives). This multidisciplinary approach is crucial to transform a scientific breakthrough into a tool for regional development, generating skilled employment, reducing dependence on imported inputs, and contributing to the technological sovereignty of the region.

Despite this potential, comprehensive research on the optimized characterization and standardized medical application of *Allium cepa*-derived silver nanoparticles against a broad range of multidrug-resistant clinical pathogens remains a significant gap.

The main objective of this study is to synthesize and characterize silver nanoparticles using *Allium cepa* extract. Secondary objectives include evaluating their antimicrobial efficacy against clinical isolates and assessing their structural stability. This study is significant as it provides a medically safe alternative to traditional antibiotics, addressing the global challenge of drug-resistant infections through sustainable pharmaceutical innovation.

II. METHODOLOGY

A. Preparation of Allium cepa Extract

The *Allium cepa* extract was obtained through the alcoholic maceration method. Initially, mature *Allium cepa* were washed three times with distilled water. The onions were then cut into small pieces to increase the contact surface with the solvent. The total mass was placed in an amber flask, to which 70° ethanol (Alkofarma) was added as the extraction solvent at a ratio of 1:5 (w:v). The mixture was subjected to constant agitation on a magnetic stirrer at 100 rpm for 15 days. At the end of the maceration process, the mixture was filtered (Whatman 42/125 mm/CAT1442-125) to separate the solid residues from the liquid phase. The resulting extract was stored at 4°C for subsequent use.

B. Preparation and characterization of AgNPs using Allium cepa extract

A precursor solution of silver nitrate was prepared by dissolving 0.3 g of $AgNO_3$ in 750 mL of distilled water, which was subjected to magnetic stirring for 10 minutes to ensure complete dissolution. Subsequently, 80 mL of the solution were distributed into 9 beakers, each placed individually on a magnetic stirrer. To each beaker, *Allium cepa* extract was added

at 3%, 5%, and 7% of the total volume, serving as both a reducing and stabilizing agent, and maintained under magnetic stirring at 300 rpm for 30 minutes at 45°C. Finally, sodium hydroxide (NaOH) was added dropwise until reaching pH values of 9, 10, and 11, measured with a pH meter (Hach HQ40D). Constant stirring was maintained until the sample changed color. The resulting material was then collected and subjected to characterization, with the entire process detailed in the flow diagram shown in Fig 1.

The optical characterization of the extract and AgNPs was performed using UV-Vis spectrophotometry (Thermo Fisher Scientific, Genesys 150, USA) in the range of 380 to 900nm.

Functional groups of the extract and AgNPs were analyzed by FTIR (Thermo Scientific Nicolet iS50) collecting 20 scans from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1}

Antimicrobial activity was evaluated using the broth microdilution method according to CLSI guidelines (CLSI, 2021). Reference strains were used: *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 29213), with 18–24h of growth. Microbial suspensions were adjusted to 0.5 McFarland (1×10^8CFU/mL) in sterile saline solution and diluted to achieve a final inoculum concentration of 1×10^5CFU/mL per well. Microplates were incubated at 36±1°C for 24–48h before growth assessment. All tests were performed in triplicate (*E. coli* and *S. aureus*).

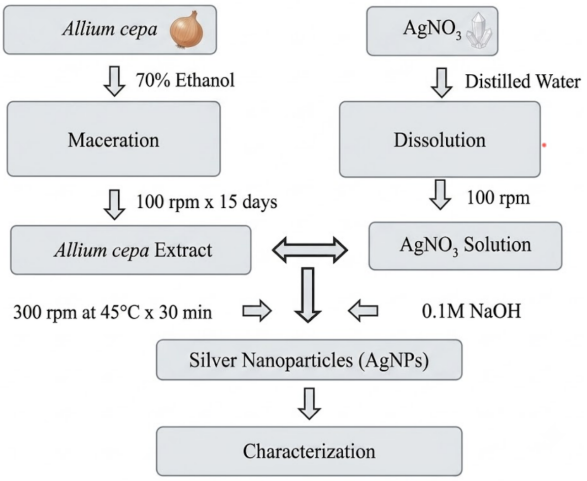


Fig. 1 Schematic representation of the green synthesis protocol for *Allium cepa*-mediated AgNPs

C. Considerations for Scalability and Technology Transfer

The synthesis protocol developed in this study was designed with industrial scalability and economic feasibility in mind. The selected parameters (temperature of 45°C, pH adjustment with NaOH, extract concentration of 3–7%, and reaction time of 30 minutes) represent operating conditions that can be replicated in batch or continuous-flow bioreactors at pilot scale, using standard equipment available in agroindustrial processing plants. The raw material (onion peel) is a low-cost residue (approximately 0.05–0.10 USD/kg in producing countries such as Mexico, Peru, and Argentina), which significantly reduces production costs compared to conventional chemical methods that employ reagents such as sodium borohydride (≈50 USD/kg). The use of 70% ethanol as extraction solvent allows for its recovery and reuse through simple distillation, aligning with the principles of green chemistry and circular economy. This preliminary analysis suggests that the production of AgNPs using *Allium cepa* extract could achieve a production cost of approximately 15–20 USD per gram of nanoparticles, competitive with commercial alternatives and with the added advantage of using renewable and non-toxic ingredients

III. RESULTS

Fig 2 shows the UV-Vis spectrum of the *Allium cepa* extract, which exhibits a dominant absorption band in the near-UV/visible region with a maximum peak at approximately 400 nm. This feature can be attributed to $\pi\rightarrow\pi^*$ and $n\rightarrow\pi^*$ electronic transitions within the aromatic rings and chromophoric groups of its secondary metabolites. This spectral pattern confirms a high concentration of bioactive compounds, including flavonoids (notably quercetin and its glycosides), soluble phenols, and hydrophilic organosulfur compounds [33], [34]. From a phytochemical and green synthesis perspective, hydroxyl (-OH) and thioester groups in these biomolecules play a dual fundamental role: they act as efficient reducing agents by donating electrons for the thermodynamically favorable conversion of metal ions to zero-valent silver ($Ag^+\rightarrow Ag^0$), while simultaneously functioning as capping agents [35]. By coordinating on the surface of newly nucleated silver cores through ligand–metal interactions and hydrogen bonding, these phytochemicals impart steric hindrance and electrostatic repulsion, preventing colloidal aggregation and stabilizing the resulting nanomaterial [36]. These findings closely align with previous literature on *Allium cepa* and other species of the genus Allium, where identical spectral signatures in the 270–320 nm range have been reported, corroborating the suitability of plant extracts for the sustainable production of silver nanoparticles without the use of toxic synthetic reagents [36], [37].

In Fig 3, the UV-Vis absorption spectrum shows a prominent and symmetric absorption band with a maximum wavelength (λ_{max}) centered at 425 nm and an absorbance intensity of 0.85 a.u. a characteristic optical signature confirming the successful synthesis of silver nanoparticles (AgNPs) [33]. This spectral profile is based on the phenomenon of Surface Plasmon Resonance (SPR), which occurs when incident electromagnetic radiation induces a collective and coherent oscillation of conduction electrons within the metallic nanostructure's conduction band [33], [34]. The presence of a sharp and well-defined peak, characterized by a narrow full width at half maximum (FWHM), suggests a narrow size distribution and good colloidal stability. Morphological

confirmation requires SEM/TEM [35]. The peak position at 425 nm closely matches values reported in the literature for the phytosynthesis of AgNPs mediated by *Allium cepa* and related species, whose reducing metabolites (flavonoids such as quercetin and organosulfur compounds) facilitate the rapid conversion of Ag^{+} ions to Ag^{0} and their subsequent stabilization [36]. Minor spectral variations observed compared to other plant extracts can be attributed to the kinetic conditions of the process—such as pH, system temperature, and the stoichiometric ratio between $AgNO_3$ precursor and capping biomolecules—parameters that directly modulate nucleation rate and final nanocrystal size [35], [37].

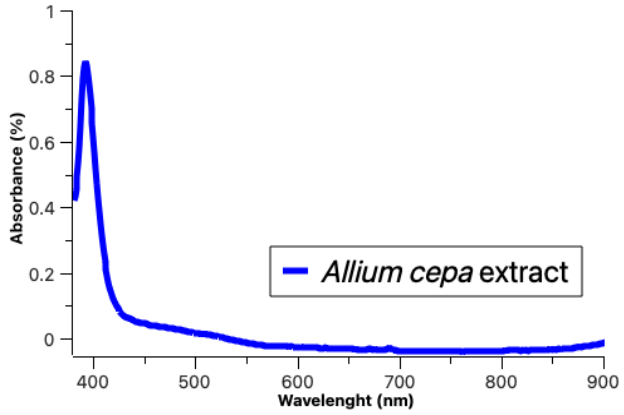


Fig. 2 UV-Vis Spectrum of *Allium cepa* Extract.

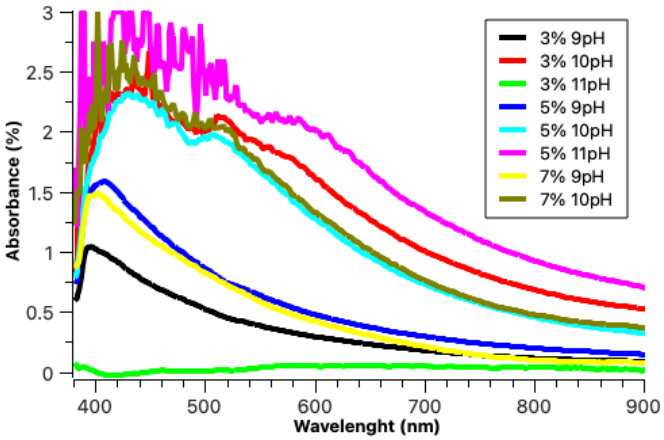


Fig. 3 UV-Vis Spectrum of Silver Nanoparticles obtained *Allium cepa* Extract as Reducing Agent.

In Fig. 4 and Fig. 5, the Fourier-transform infrared (FTIR) spectroscopy analysis of the ethanolic Allium cepa extract and the synthesized silver nanoparticles (AgNPs), respectively, is presented. The results confirm the direct involvement of phytochemical secondary metabolites both in the redox bioreduction process ($Ag^{+} \rightarrow Ag^{0}$) and in colloidal passivation or capping [33]. The spectrum of the crude plant extract shows a broad and intense band centered around 3320 cm^{-1}, corresponding to –OH stretching vibrations of phenolic compounds and flavonoids (notably quercetin), superimposed with –NH stretching of protein amides [38]. Characteristic peaks are also observed at 2925 cm^{-1} and 2850 cm^{-1} (aliphatic C–H stretching), 1635 cm^{-1} (C=O carbonyl stretching and amide I), 1385 cm^{-1} (in-plane deformation attributable to organosulfur bonds C–S and S=O, typical of volatile derivatives such as allicin), and 1045 cm^{-1} (C–O stretching of glycosides and reducing sugars) [34]. After AgNP formation, a marked shift of the −OH band to 3280 cm^{-1} and a clear shift of the carbonyl (C=O) band from 1635 to 1615 cm^{-1} are evident, confirming electron transfer and redox coupling interactions of hydroxyl and carbonyl groups during nanocrystal nucleation [34], [37]. Finally, the presence of stretching signatures in the 1000–1400 cm^{-1} range corroborates that sulfur-containing and polyphenolic biomolecules remain adsorbed on the Ag^{0} core surface through ligand–metal coordination interactions between heteroatoms (O, S, N) and the metallic surface, forming the steric and electrostatic capping layer necessary to prevent aggregation [37], [39].

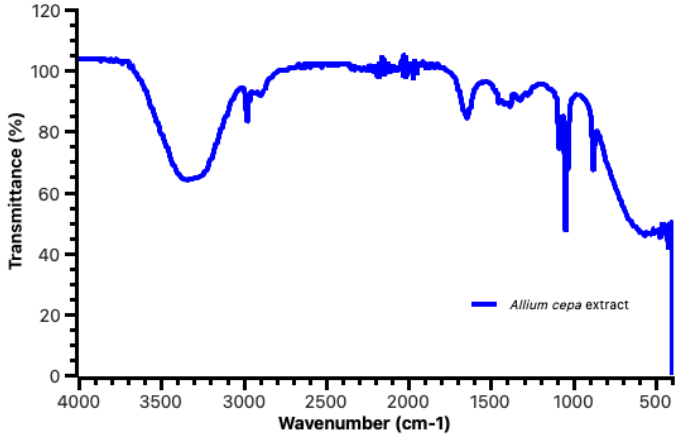


Fig. 4 FTIR Spectrum of *Allium cepa* Extract

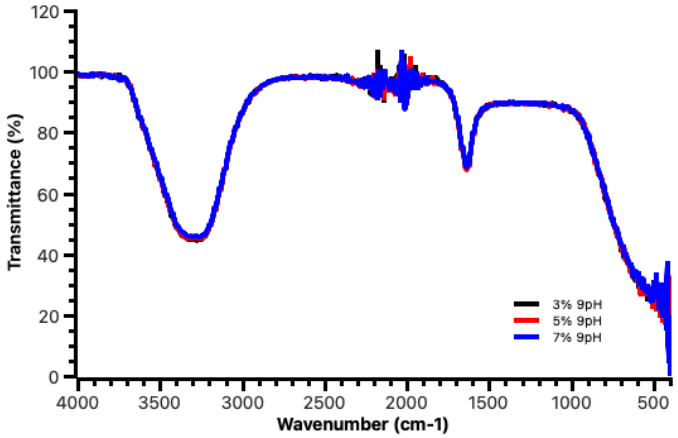


Fig. 5.FTIR Spectrum of Silver Nanoparticles Obtained Using *Allium cepa* Extract as Reducing Agent

The antimicrobial activity evaluation shown in Fig. 6 indicates that silver nanoparticles synthesized using Allium cepa extract exhibit inhibitory capacity against the tested

microorganisms. The inhibition zones reached up to 14 mm for Escherichia coli and up to 16 mm for Staphylococcus aureus (16, n = 3; Fig. 6, Table 4). Both strains were susceptible, with slightly larger zones observed for *E. coli* than for *S. aureus.* Mechanistically, the bactericidal action of AgNPs is attributed to a multifactorial process driven by sustained release of Ag^+ cations, disruption of plasma membrane permeability, and intracellular generation of reactive oxygen species, leading to oxidative stress, protein denaturation, and enzymatic inactivation through affinity to thiol groups [35]. Furthermore, the organic coating derived from Allium cepa extract — composed of flavonoids such as quercetin and organosulfur compounds acting as reducing and stabilizing agents (capping agents) — exerts a synergistic effect by enhancing biocompatibility and bioadhesion of the particles to the bacterial surface [36], [37].

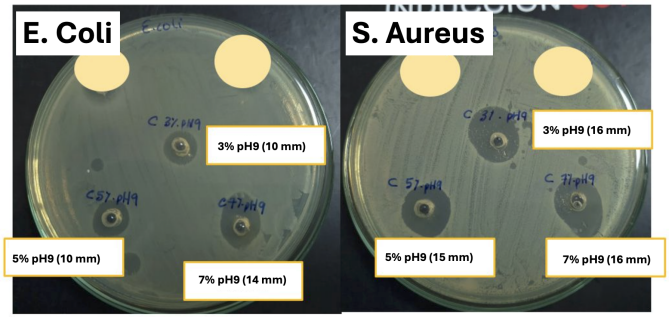


Fig. 6 Antimicrobial Activity of Silver Nanoparticles Obtained Using *Allium cepa* Extract as Reducing Agent

Innovation Potential and Sectoral Applications

The results obtained position AgNPs synthesized from *Allium cepa* extract as an innovative product with multiple commercial application pathways:

Active food packaging sector: The demonstrated antimicrobial activity (~14 mm against *E. coli*) suggests that these AgNPs can be incorporated into polyethylene or chitosan films to extend the shelf life of perishable products (fruits, meats, dairy), reducing postharvest losses that reach 30–40% of production in Latin America.

Antimicrobial coatings: The colloidal stability and biocompatibility of AgNPs make them suitable for the development of paints and coatings for high-contact surfaces (hospitals, schools, public transport), addressing the issue of nosocomial infections.

Community-based business model: The simplicity of the protocol and the availability of raw material enable the design of cooperative business models where rural onion-producing communities can establish small-scale production plants (microenterprises), generating complementary income and fostering local development.

Scalability and Sustainable Pharmaceutical Innovation: The operating conditions (45 °C, 30 min, pH 9–11) are compatible with industrial scaling in stirred-tank reactors, eliminating the need for toxic solvents. This green route represents a sustainable pharmaceutical innovation, as it not only produces biocompatible antimicrobials but also valorizes onion peel waste, reducing the environmental footprint of nanoparticle manufacturing. Future pilot-scale studies will focus on optimizing yield and purity for clinical translation.

V. CONCLUSIONS

Successful Green Synthesis: The *Allium cepa* extract enabled the production of stable silver nanoparticles (AgNPs), confirmed by SPR at 425 nm in UV-Vis. Its phytochemicals (flavonoids, phenolic compounds, and organosulfur compounds) acted as reducing and stabilizing agents, as evidenced by FTIR shifts in −OH and C=O bands.

Differential Antimicrobial Activity: AgNPs showed greater inhibition against E. coli (Gram-negative, ~14 mm) than against S. aureus (Gram-positive, ~16 mm), attributed to the higher permeability of the Gram-negative outer membrane.

Multifactorial Mechanism: The bactericidal efficacy combines Ag^+ ion release, reactive oxygen species (ROS) generation, disruption of membrane permeability, and synergism with phytochemical capping agents that enhance bioadhesion.

Sustainable Advantage and Applications: Green synthesis with *Allium cepa* represents an ecological, biocompatible, and cost-effective alternative to conventional toxic methods, with potential applications in medicine (antimicrobials), agriculture (fungicides), and the food industry (active packaging).

Entrepreneurship Potential: Green synthesis of AgNPs from onion waste offers a sustainable business opportunity, with competitive production costs and applications in high-demand sectors (food, health), positioning it as an innovative product for startups and cooperatives in onion-producing regions.

Contribution to Regional Development: This work demonstrates that green nanotechnology, based on local resources and agro-industrial residues, can drive endogenous technological development in Latin America, reducing dependence on imported inputs, generating skilled employment, and promoting circular economy as a sustainable development model.

This preliminary study focused on UV-Vis and FTIR. SEM/TEM, DLS, and XRD were not performed. Therefore, claims regarding spherical morphology and monodispersity are preliminary. Future work will include these techniques

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