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Green-Synthesized AgNPs for Bacterial Efficacy and Sustainable Development Goals

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Abstract

A green synthesis technique, which is economical and environmentally sustainable, was used to synthesize AgNPs, and several methods were employed to characterize the nanoparticles, such as UV-Vis spectroscopy, SEM, TEM, and FTIR. The produced AgNPs demonstrated noteworthy antibacterial and antifungal attributes. Unique absorption peaks were observed in the UV-Vis spectra, indicating successful AgNP synthesis. According to SEM and TEM examinations, the nanoparticles had a steady average size of 48nm and were spherical. When the antibacterial activity was tested against several bacterial strains, it showed significant inhibitory effects. This research underscores the potential of AgNPs in various applications, including medical devices, environmental remediation, and consumer products, to combat antibiotic resistance and infection control for good health and well-being, as outlined in Sustainable Development Goal 3 (SDG3). AgNPs can act as efficient catalysts for various chemical reactions, including organic synthesis, environmental remediation, and energy storage, SDG 12 (Responsible Consumption and Production). Green-synthesized AgNPs can be used to remove pollutants from water and soil (SDG 6: Clean Water and Sanitation). This study investigates the synthesis, characterization, and utilization of silver nanoparticles (AgNPs), emphasizing environmentally sustainable production methods and providing valuable perspectives for future developments in nanomedicine and associated fields.

Keywords: AgNP synthesis methods, Characterization, Environmental remediation, Biological activity, Bacterial efficacy.

INTRODUCTION

Materials in nano-confines (1–100 nm) have remarkable differences in parcels compared to bulk materials. These differences exist in the physical and structural parcels of particles, molecules, and bulk paraphernalia owing to differences in physicochemical parcels and face-to-volume rates[1]. With advances in nanotechnology, numerous nanomaterials with unique properties have emerged, opening new avenues for research. Metal nanoparticles, including silver, platinum, and gold, are used for various purposes[2,3]. AgNPs have been used extensively because of their unique physical and chemical characteristics, including electrical conductivity, thermal, optical, antimicrobial, and natural properties. AgNPs are widely used in biomedical applications, such as in crack dressings, antiseptic fabrics, creams, and sprays. AgNPs affect microorganisms through membrane disruption and enzymatic inhibition. Researchers have developed nanomaterials with distinct size-controlled physicochemical features and applications[6]. AgNPs are significant for their operations in healthcare, medicine, photothermal treatments, visual operations, catalytic processes, energy transfer, solar cells, optoelectronics, and environmental applications.[7] Biological methods are safe, provident, doable, and ecologically sound, with downsides of time consumption and lower influence on size, shape, and liquid structure[8]. Among metallic rudiments, Ag is a noble metal that is central to antibacterial research. This review emphasizes the outlook, development, antibacterial functioning & mechanism, characterization methods, factors affecting bactericidal functioning, antimicrobial relevance, and future perspectives for green nanotechnology-based AgNPs in antibacterial therapeutic applications and infection control for SDG-39.

Theoretical framework

Silver nanoparticles (AgNPs) have attracted attention from researchers because of their defense against microorganisms and drug resistance against commonly used antibiotics[10]. The characteristics of AgNPs have made them applicable in biomedical, drug delivery, water treatment, and agrarian fields[11]. AgNPs are used in ink bonds, electronic devices, and pastes because of their high conductivity[12]. AgNPs have been synthesized using various physicochemical methods, such as chemical reduction, gamma shaft radiation[13], microemulsion, electrochemical system[14], laser ablation[15], autoclave, microwave oven roasting, and photochemical reduction. These methods have effective yields but are limited by toxic chemicals, high costs, and energy requirements. Given these downsides, cost-effective and energy-efficient approaches for AgNP emulsions using microorganisms, plant extracts, and natural polymers as reducing and capping agents are emerging. The combination of nanotechnology and green chemistry will expand biologically and cytologically compatible metallic nanoparticles[16,17,18].

Phytochemicals in plant leaves, including flavonoids, alkaloids, ketones, carboxylic and ascorbic acids, tannins, amides, and phenols, drive the development of metal nanomaterials. These substances reduce metal salts to produce metal nanoparticles[19] and exhibit antibacterial and antioxidant properties. Green synthesis of nanoparticles has lower toxicity and higher biocompatibility than chemical synthesis because of the longer nanomaterial half-life and increased efficiency[20]. Although the green synthesis of silver nanoparticles has been extensively studied, particularly regarding the synthesis using bacteria and fungi, to our knowledge, there is a lack of detailed information on environmentally friendly synthesis using plant extracts or their antiviral, antifungal, antimicrobial, and anticancer qualities[21].

The plant species used for the eco-friendly synthesis of AgNPs are listed in Table 1. Field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) are common methods for confirming nanoparticle formation and examining their shape, size, and surface area. The diameters of the reported particle sizes ranged from 5 to 100 nm, except for one. Their shapes included spherical, face-centered cubic (FCC), quasi-spherical, and occasionally truncated or rod-like forms. Nanoparticles exhibit biological and catalytic actions, such as antibacterial, antioxidant, anticancer, and photocatalytic effects, in addition to structural characterization. This indicates that Ag nanoparticles can be widely used in biomedical and environmental fields.

Table 1: Silver nanoparticles, their characterization, and applications

Sr. No	Metal nanoparticles	Reducing agent or extract	Characterization	Particle characteristic	Applications	Author	References
1	AgNPs	Sambucusebulus	FTIR, UV-Vis XRD HPLC	Size 18.6nm Shape-FCC	Antioxidant,& antibacterial activity	Karan T. *et al.,* (2024)	[22]
2	AgNPs	Rubus discolor leave	UV- Vis, TEM FTIR EDX	Size-37 nm Shape- predominantly spherical	Antibacterial activity against Escherichia coli and Pseudomonas aeruginosa	Ghasemi S. *et al.,* (2024)	[23]
3	AgNPs	Ocimumtenuiflorum and Azadirachtaindica	UV- Vis XRD	Shape- FCC Size- 21 nm	S.aureus, E. coli, P.aeruginosa	Reen G. K., *et al.,* (2024)	[24]
4	AgNPs	Azadirachtaindica, Syzygiumaromaticum	UV-Vis,		Against Enterococcus	Chandran N. *et al.,* (2024)	[25]
5	AgNPs	Terminaliabellirica	UV- Vis, FTIR, XRD, FESEM	Size- 44.5 nm Shape-FCC	Antimalarial activity	Singh S. *et al.,* (2024)	[26]
6	AgNPs	Pimpinellaanisum aqueous seed extract	UV- Vis FTIR XRD	Shape- spherical Size– 20.18nm, 21.00nm, 40.08nm	Antibacterial against a strain of Escherichia coli	Barabadi H. *et al.,*(2023)	[27]
7	AgNPs	Moringaoleigera leaf extract	UV- Vis, FTIR, TEM	Size – 24 -40 nm	antibacterial Staphylococcus aureusATCC6538 and pseudomonas aeruginosa ATCC9027	Shaaban T. M. *et al.,* (2023)	[28]
8	Ag	NPs	Equisetum diffusum extract	UV- Vis FTIR, DLS, SEM EDX	Size- 62.6 nm Antibacterial L.monocytogenes and E. coli	Jabbar A. *et al.,*(2023)	[29]
9	AuNPs	Gelidiellaacerosa	UV-Vis FTIR	Size- 5-20 nm Shape- Spherical	Antibiotic against Staphylococcus aureus and,G. acerosa	Subbulakshmi A. *et al.,* (2023)	[30]
10	AgNPs	Green tea leaf extracts	UV- Vis., FTIR	Size- 30 – 150 nm Shape-quasi-spherical	High killing ability for bacteria (E. Coli)	Parvathalu K., *et al.,* (2023)	[31]
11	AgNPs	Eucalyptus camaldulensis and Terminaliaarjuna extracts	UV- Vis, SPR, SEM , FTIR	Size- 23nm, 13 nm, 42 nm	Bacillus subtilis, Staphylococcus aureus, Pasteurellamutocida	Liaqat N. *et al.,*(2022)	[32]
12	AgNPs	Tridaxprocumbens plant (TNP) extracts	TEM, Zeta potential FTIR, HRLC- MS HPLC	Size- 23.17 nm Shape- FCC	Against Anticancer Escherichia coli, Shigella spp., Aeromonas spp.	Pungle R. *et al.,*(2022)	[33]
13	AgNPs	ConocarpusLancifolius fruit extracts	UV- Vis, FTIR, XRD	Size- 22.5 nm, Shape – spherical	Anticancer and Antibacterial Streptococcus p., S. Aureus.	Oves M. *et al.,*(2022)	[34]
14	AgNPs	Syzygiumcumini fruit extract	UV- Vis, FTIR, XRD, SEM	Size- 47 nm Shape- FCC	Inhibit free radical orientation diseases., (G +ve& G –ve) bacteria	Chakravarty A. *et al.,*(2022)	[35]
15	AgNPs	Cassia tora seed extracts	UV- Vis, FTIR, SEM, XRD	Size- 55.80 nm, 58 nm, 61.06 nm, 63.26 nm, 64.80 nm	Antibacterial efficacy against S. aureus.,	Nawabjohn M. S. *et al.,*(2022)	[36]
16	AgNPs	East extract, malt extract	UV- Vis, FTIR, TEM, XRD	Size- 13.2 nm Shape – spherical	Antibacterial & cancer activity against (MCP) Escherichia coli, Klebsiella pneumonia	Wypij M. *et al.,*(2021)	[37]
17	AgNPs	Cucumber leaf and rice husk extract	—–	———	Compared study between g-AgNPs& Chem. AgNPs Strong antibacterial activity Escherichia coli	Zhang H. *et al.,*(2021)	[38]

18	AgNPs	Areca catechu extract	UV- Vis, SEM, DLS, FTIR	Size – 25 nm Shape-spherical (round)	Against antibiotic-resistant bacteria	Choi S. J. *et al.*,(2021)	[39]
19	AgNPs	Berberis vulgaris B. nigra, Capsella bursa-pastoris, L. angustifolia plant extract	UV- Vis, FTIR, TEM, XRD, PCCS	Size- 46.1 nm Shape-spherical, truncated octahedron	Antibacterial activityL.monocytogenes) (gram +ve	Salayova A. *et al.*,(2021)	[40]
20.	AgNPs	Grapefruit peel extract	UV- Vis, FTIR	Size – 13.56 nm	Staphylococcus A., Enterococcus faecalis & S. aureus	Arsene M.M.J. *et al.*,(2021)	[41]
21	AgNPs	Onion (O), Tomato (T), Acacia catechu (C) alone, and Mixed COT extracts	UV- Vis, FTIR, TEM, XRD, DLS	Size – 25 nm Shape–FCC	PhytocatalitiicalDeradation of methyl orange (MO), methyl red (MR), &congo red (CO)	Chand K. *et al.*, (2020)	[42]
22	AgNPs	Brillantaisiapatula, Cross opreryxfebrifuga, and Sennasiamea leaf extract	UV- Vis, FTIR, XRD, TEM	Size- 17 nm Shape- spherical	(G +ve and G – veBect.) Staphylococcus A., Escherichia coli & Pseudomonas A.	Kambale K. E. *et al.*, (2020)	[43]
23	AgNPs	OcimumCanum Sims leaf extract		XRD, SEM	Size – 15.72 nm Shape- spherical and rod shape	Escherichia coli Tailor G. *et al.*,(2020)	[44]
24	AgNPs	flower extract of Aervalanata	UV- Vis, FTIR, AFM, SEM, TEM		Size- Shape –	Bacterial activity against Klebsiellaplanticola Kanniah P. *et al.*,(2020)	[45]
25	AgNPs	Gymnemasylvestre leaf extract	UV- Vis, FTIR, XRD, TEM,		Size – 20 nm & 30 nm Shape – FCC	Staphylococcus aureus and Escherichia coli Rajkumar P. V. *et al.*, (2020)	[46]

Synthesis methods for nanoparticles

Top-Down and Bottom-Up Methods: The synthesis of nanoparticles through biological systems is not only advantageous but also imperative for advancing sustainable technology. This method offers unparalleled benefits, including high-yield production, scalability, non-toxicity, and precise morphologies. It is crucial to pioneer novel methods for nanoparticle production, and green synthesis techniques are at the forefront of this innovation. These techniques are not only straightforward and safe but also environmentally friendly, making them indispensable in modern science[47]. Saratale *et al.,* have meticulously reviewed various green nanoparticle synthesis techniques, highlighting their transformative applications in agriculture and biomedicine[48]. The synthesis of green nanoparticles employs two distinct approaches: top-down and bottom-up approaches. The top-down approach involves mechanical methods to form larger nanoparticles, whereas the bottom-up approach, which is synonymous with green synthesis, utilizes acids to reduce the particle size. It is essential to integrate the bottom-up method with complex analysis when employing the top-down approach to maximize efficiency and effectiveness[49]. Embracing these green synthesis methods is not just a choice but a necessity for a sustainable future.

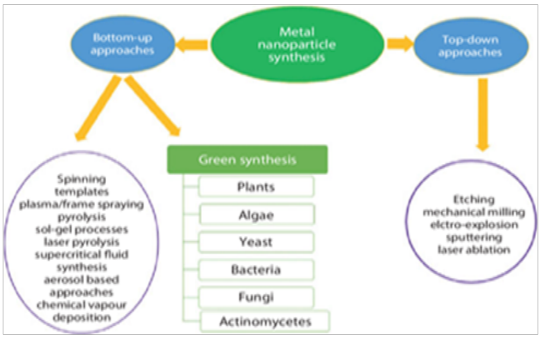


Fig. 1. Top-down and bottom-up synthesis[49]

Green synthesis

Embracing the future of sustainable technology involves the environmentally friendly synthesis of AgNPs. By utilizing a solution of silver metal ions and an organic reducing agent, nanoparticle production can be revolutionized without the need for external stabilizing and capping agents. Remarkably, the natural components found in plants, such as flavonoids, alkaloids, ketones, aldehydes, amides, and ascorbic acid, serve as effective agents, making the process not only efficient but also eco-friendly. The synthesis of AgNPs is not just a possibility; it is a reality that harnesses the power of nature[50].

The cornerstone of this innovative synthesis is Ag^+ ions, which are readily available in various water-soluble silver salts. Among these, the aqueous $AgNO_3$ solution stands out, with an optimal Ag^+ ion concentration range of 0.1–10nm, most commonly at 1nm. This precise concentration ensured the successful development of AgNPs, paving the way for advancements in nanotechnology. By adopting this method, researchers can lead the charge in creating a sustainable future, demonstrating that cutting-edge technology and environmental responsibility can go hand in hand[51].

AgNP synthesis using plant extract

The green synthesis of AgNPs using plant extracts is not just an advancement in nanotechnology; it is a revolutionary leap forward, offering a sustainable and eco-friendly alternative to traditional methods of synthesis. Harnessing the power of various plant extracts from leaves, flowers, bark, roots, and stems, especially from medicinal plants like Azadirachta indica[51], Aloe vera[52], Ocimum tenuiflorum[53], Emblica officinalis[54], Tinospora cordifolia[55], Cocos nucifera[56], and common spices such as piper nigrum[57], serves as a potent and natural solution. These plant components underwent a meticulous cleaning process, first with tap water and then with distilled water, to ensure their absolute purity. After drying, they were either ground into a fine powder or used directly to create extracts with varying pH values, while enhancing the stability of AgNPs, with protein metabolites and chlorophyll acting as effective agents[58]. The efficiency of this process is undeniable, as evidenced by the synthesis of spherical AgNPs averaging 20nm in a mere 40min using 60 mL of plant leaf extract and 10 mL of $AgNO_3$ at 60°C. Prathinha *et al.,*[59] further substantiated this method by successfully synthesizing AgNPs using Azadirachtaindicaand Ocimumtenuiflorum green extracts. The striking visual transformation from green to dark brown is a definitive indicator of successful AgNP formation (Fig. 2). Importantly, higher concentrations of plant extracts significantly accelerate the synthesis rates 25, while factors such as pH, temperature, optical activity, and $AgNO_3$ concentration are crucial for optimizing production. The precise collection of AgNPs for characterization was ensured by centrifuging the silver nitrate and plant solutions[24]. Neem and *Ocimum tenuiflorum* extracts have been extensively studied, with neem plants exhibiting extraordinary antibacterial and antifungal properties, offering promising applications in bacterial treatment, as illustrated in Fig. 3. This innovative approach to AgNP synthesis champions environmental sustainability and holds immense potential for propelling medical and technological advancements[60,62].

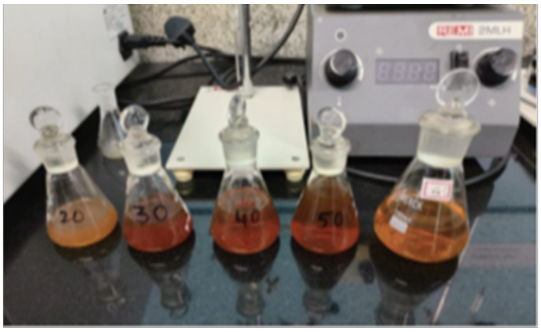
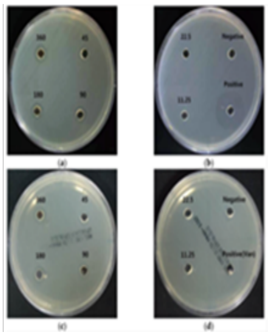


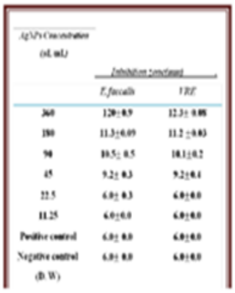
Fig. 2. Tulsi extract explanation setup during AgNP formation[59]

This groundbreaking approach not only underscores the remarkable versatility of plant materials but also highlights their pivotal role in advancing nanotechnology. The evidence is clear: plant-based synthesis of AgNPs is not just a possibility but a revolutionary step forward in the field[63].

Antimicrobial properties of the produced agnps
Well Diffusion Assay

The antibacterial efficacy of AgNPs was rigorously evaluated using the agar well diffusion assay, a method that leaves no room for doubt. The results, measured by inhibition zones (mm) in 6 mm wells on Muller-Hinton agar, were nothing short of compelling. The particles, serially diluted 2-fold from 360 μL/mL to 11.25 μL/mL64, demonstrated a formidable antibacterial effect. *E. faecalis*, a notorious *Gram-positive* cocci bacterium, leading cause of enterococcal infections in humans and a prevalent pathogen in hospitals, often found in the urinary tract, bloodstream, and surgical sites. The positive control, vancomycin, exhibited its well-documented antibacterial action against *E. faecalis*, with an impressive inhibition zone of 27.0 ± 0.0 mm. However, the challenge of vancomycin-resistant enterococci (VRE)[65], a global threat, remains unyielding, as no inhibition zone was observed for either VRE or *E. faecalis* strains. The AgNPs data, as illustrated in Fig. 3, reveal a strain with sustained release, greater stability, tensile strength, nanoscale porosity, flexibility, and dominant antimicrobial efficacy against both *Gram-negative* and *Gram-positive* strains.





AgNPs Concentration (ul mL)	Inhibition zone(mm)	
	E.faecalis	VRE
360	120±0.5	12.3± 0.08
180	11.3±0.09	11.2 ±0.03
90	10.5± 0.5	10.1±0.2
45	9.2± 0.3	9.2±0.1
22.5	6.0± 0.3	6.0±0.0
11.25	6.0±0.0	6.0±0.0
Positive control	6.0± 0.0	6.0±0.0
Negative control (D.W)	6.0± 0.0	6.0±0.0

Fig. 3. Antibacterial effects of AgNPs using *A. catechu* against *E. faecalis* and VRE. (a,b) Inhibition zone of AgNPs against *E. faecalis*; (c,d) inhibition zone of AgNPs against VRE62

This highlights the potential of microemulsions in wound healing applications[66]. *P. aeruginosa*, a *Gram-negative* bacterium notorious for its green pigment pyocyanin, poses severe health risks, including meningitis, septicemia, post-transplant infections, persistent pneumonia, and urinary tract infections[67]. The rise of multidrug-resistant *Pseudomonas aeruginosa* (MRPA) is a serious public health concern, escalating morbidity and mortality in hospitalized patients. Alarmingly, MRPA showed no inhibition zone for gentamicin, whereas P. aeruginosa exhibited a substantial inhibition zone of 25.0±0.7mm diameter. Notably, both bacteria displayed concentration-dependent inhibition zones, with *P. aeruginosa* treated with AgNPs achieving a slightly larger inhibition zone than MRPA. The results, as depicted in Fig. 4 and the accompanying Table, underscore the potential of AgNPs in combating these formidable pathogens[65].

Characterization

The characterization of the synthesized AgNPs using techniques such as Fourier transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), ultraviolet-visible spectroscopy (UV-Vis), X-ray diffraction (XRD), and scanning electron microscopy (SEM) is critical for revealing details of size, shape, and surface charge[22,78]. Dynamic light scattering (DLS) and zeta potential methods are essential for characterizing antibacterial agents, providing crucial insights into their application[42,66,79]. Atomic force microscopy (AFM) and high-performance liquid chromatography (HPLC) provide additional information for characterizing AgNPs. The transformation of Ag^+ to Ag° in the aqueous phase is evidenced by a band in the silver colloid spectra at approximately 410nm[33]. As the silver concentration increased, the absorption band sharpened, and a red shift from 402 to 407 nm occurred (Fig. 4) when the $AgNO_3$ concentration increased from 250 to 1000 mg/dm³, indicating larger silver aggregates and increased particle size. The TEM images confirmed the transformation of spherical silver particles into prismatic structures[67]. The size, morphology, and surface charge of nanocarriers are pivotal determinants of their physical stability and function. Smaller particles with larger surface areas influence drug release, whereas the surface charge affects the interactions between the biological environment and bioactive compounds[70]. The safety, behavior, and efficacy of biodistribution depend on these factors. A comprehensive description of AgNPs is essential to assess their functional elements.[68]

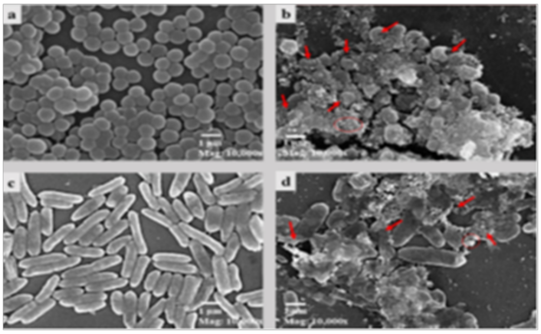


Fig. 4. Scanning electron microscopy images of *S. aureus* (control and AgNP-treated) and *P. aeruginosa* (control and AgNP-treated). Red arrows indicate bacterial cell distortions, and the red circle shows nanoparticle accumulation on cells[62]

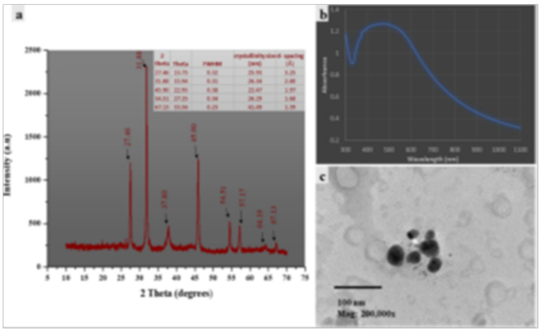


Fig. 5(a). XRD pattern showing peaks at 2-theta angles. (b) The curve shows the absorption feature, indicating the energy band gap. (c) TEM image reveals the spherical morphology and size distribution[62]

Applications of green synthesized silver nanoparticles for health and well-being, SDG 3

Green-synthesized AgNPs have gained attention owing to their unique properties and applications across fields. Their environmentally friendly synthesis using biological agents offers advantages over traditional chemical methods of synthesis. AgNPs exhibit antimicrobial properties against bacteria, fungi, and viruses, making them promising candidates for use in wound dressings, medical devices, and water purification[69,79]. Green-synthesized AgNPs have applications in drug delivery, biosensing, and cancer therapy, enabling targeted drug delivery and cancer cell apoptosis[70].

SDG 12 Catalysis: AgNPs are efficient catalysts in chemical reactions, including organic synthesis and environmental remediation. Their surface area and electronic properties enhance their catalytic activity[71,78].

SDG 6, Environmental Remediation: Green-synthesized AgNPs remove pollutants from water and soil by adsorbing heavy metals and organic contaminants[72,73,76,77].

Textile Industry: AgNPs incorporated into textiles provide antimicrobial properties, odor resistance, and UV protection, improving fabric hygiene and durability[74,75].

Future prospects of green synthesized silver nano-particles

Green-synthesized AgNPs represent a groundbreaking advancement with transformative potential in multiple industries, including personalized medicine, sustainable agriculture, and environmental remediation. These nanoparticles are not just an option; they are a necessity for achieving SDG-3 by promoting the good health and well-being of the population. In personalized medicine and tissue engineering, AgNPs offer unparalleled opportunities for innovation and improvements. As sustainable alternatives to chemical pesticides, they promise to revolutionize agriculture and ensure food security while protecting the planet. Moreover, their application in air purification systems and smart textiles for healthcare monitoring is expected to redefine industry standards. However, to fully harness these benefits, it is imperative to establish standardized protocols for their synthesis, application, and disposal. This will ensure safety and minimize environmental impacts. Furthermore, rigorous research on the long-term effects of AgNPs on human health and the environment is essential to determine safe usage levels. The time to act is now; embracing AgNPs is not just a choice but a strategic imperative for a sustainable future.

CONCLUSION

Characterization of green-synthesized AgNPs is imperative to unlock their potential in biomedical applications. Techniques such as SEM, TEM, UV-visible spectroscopy, FTIR, XRD, dynamic light scattering (DLS), and zeta potential measurements provide insights into the size, shape, morphology, and surface charge of these nanoparticles. The spectral shifts and morphological transformations from spherical to prismatic structures indicate changes in particle size and aggregation, which influence their functional properties, including drug release behavior and biodistribution. Advanced techniques such as atomic force microscopy (AFM), high-performance liquid chromatography (HPLC), and zeta potential measurements for antibacterial characterization highlight the role of surface charge in AgNP-biological interactions. Smaller particle sizes and optimal surface charges enhance AgNP efficacy by improving their interactions with bioactive compounds and refining their distribution. Therefore, a comprehensive characterization of AgNPs is essential for optimizing their application in antimicrobial treatments and ensuring their stability in biomedical contexts.

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