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Green Synthesis of Silver Nanoparticles; A Sustainable Approach with Diverse Applications

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Abstract Silver nanoparticles (AgNPs) have garnered significant attention in recent years due to their unique properties and diverse applications across various industries. This review provides an overview of the synthesis methods, characterization techniques, applications, regulatory guidelines, and challenges associated with AgNPs. Green synthesis routes, utilizing natural extracts or biomolecules, have emerged as environmentally sustainable alternatives for producing AgNPs with reduced environmental impact. Characterization techniques such as spectroscopy, microscopy, and chromatography are employed to analyze the physicochemical properties of AgNPs and ensure their quality and stability. AgNPs find applications in biomedical, environmental, and consumer product sectors, including wound dressings, water purification filters, cosmetics, and medical devices, owing to their antimicrobial, catalytic, and optical properties. Regulatory guidelines play a crucial role in ensuring the safe and responsible use of AgNPs, addressing concerns related to biocompatibility, toxicity, and environmental impact. However, challenges remain in standardization, scalability, and long-term safety assessment of AgNP-based products. Future research efforts should focus on optimizing synthesis methods, enhancing characterization techniques, and addressing regulatory gaps to unlock the full potential of AgNPs while ensuring their safety and sustainability. Overall, AgNPs offer promising opportunities for addressing global challenges and driving technological innovation across diverse sectors.

Keywords Silver nanoparticles, Green synthesis, Plant extracts, Microorganisms, Characterization, Biomedical applications, Environmental remediation, Catalysis

1. Introduction

In recent decades, the synthesis and application of nanoparticles have emerged as a forefront area of research, driven by the unique physicochemical properties exhibited by these nanoscale materials. Among various types of nanoparticles, silver nanoparticles (AgNPs) have garnered immense interest owing to their exceptional optical, electrical, and antimicrobial properties. These properties make AgNPs versatile candidates for a wide range of applications spanning biomedical, environmental, and industrial domains [1]. Traditional methods for synthesizing AgNPs often involve the use of chemical reagents and harsh reducing agents, which pose significant environmental and health concerns due

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to the generation of hazardous by-products and the consumption of non-renewable resources. In this context, the development of green synthesis approaches for AgNPs has gained prominence as an environmentally benign and sustainable alternative [2].

Green synthesis methods utilize natural sources such as plant extracts, microorganisms, and biopolymers as reducing and stabilizing agents for the fabrication of AgNPs. These methods offer several advantages over conventional chemical approaches, including: Environmentally Sustainable; Green synthesis routes minimize the use of toxic chemicals, organic solvents, and energy-intensive processes, thereby reducing the environmental footprint associated with nanoparticle production. Green-synthesized AgNPs exhibit enhanced biocompatibility and reduced cytotoxicity compared to chemically synthesized counterparts, making them suitable for biomedical applications such as drug delivery, imaging, and tissue engineering [3, 4].

Natural sources for green synthesis are abundant, renewable, and cost-effective, enabling scalable production of AgNPs with minimal capital investment. Green synthesis methods offer precise control over the size, shape, and surface chemistry of AgNPs through modulation of reaction parameters, enabling customization for specific applications [5]. The utilization of plant extracts and microbial systems for AgNP synthesis capitalizes on the inherent reducing potential of bioactive compounds present in these natural sources, including polyphenols, flavonoids, terpenoids, and proteins. The synthesis mechanism typically involves the reduction of silver ions (Ag^+) to metallic silver (Ag^0) nuclei, followed by their subsequent growth and stabilization into nanoparticles through capping or complexation with biomolecules [6].

Moreover, green-synthesized AgNPs exhibit enhanced antimicrobial activity against a broad spectrum of pathogens, making them promising candidates for combating antimicrobial resistance and infectious diseases. Additionally, their catalytic, optical, and electrical properties render them valuable in diverse applications such as catalysis, sensing, electronics, and environmental remediation. This comprehensive review aims to provide a detailed analysis of the green synthesis approaches, characterization techniques, and multifaceted applications of AgNPs [7]. By elucidating the mechanisms underlying green synthesis routes and exploring the wide-ranging opportunities enabled by green-synthesized AgNPs, this review seeks to contribute to the advancement of sustainable nanotechnology and its integration into various scientific and technological endeavors [8].

2. Green Synthesis Techniques

The synthesis of silver nanoparticles (AgNPs) through green routes encompasses a diverse array of methodologies leveraging natural sources such as plant extracts, microorganisms, and biopolymers. These approaches offer sustainable and eco-friendly pathways for nanoparticle fabrication, characterized by reduced environmental impact, enhanced biocompatibility, and facile scalability [9]. This section provides a comprehensive exploration of the mechanisms, influencing factors, and applications of green synthesis techniques for AgNPs [10].

2.1. Plant-Mediated Synthesis

Mechanistic Insights

Plant-mediated synthesis of AgNPs involves the reduction of silver ions (Ag^+) to metallic silver (Ag^0) in the presence of phytochemicals present in plant extracts [11, 12]. Bioactive constituents such as polyphenols, flavonoids, terpenoids, and proteins serve as both reducing and stabilizing agents, orchestrating the nucleation and growth of AgNPs. The synthesis mechanism typically proceeds through redox reactions, wherein the phenolic hydroxyl groups of phytochemicals donate electrons to Ag^+ ions, leading to the formation of AgNPs and oxidation of the reducing agents, **Figure 1** [13].

Factors Influencing Synthesis

Several parameters profoundly influence the synthesis process and properties of green-synthesized AgNPs [14-18]:

a. Plant Species and Extract Composition: Different plant species harbor distinct phytochemical profiles, influencing the reducing potential and capping efficiency of the extract. Variations in solvent composition, extraction method, and plant growth conditions further modulate the composition and activity of bioactive constituents.

b. Reaction Conditions: Factors such as pH, temperature, reaction time, and Ag^+ ion concentration dictate the kinetics and thermodynamics of nanoparticle formation. Optimal conditions must be tailored to maximize nanoparticle yield, size uniformity, and colloidal stability.

c. Additives and Catalysts: Incorporation of additives such as co-reducing agents, stabilizers, or catalysts

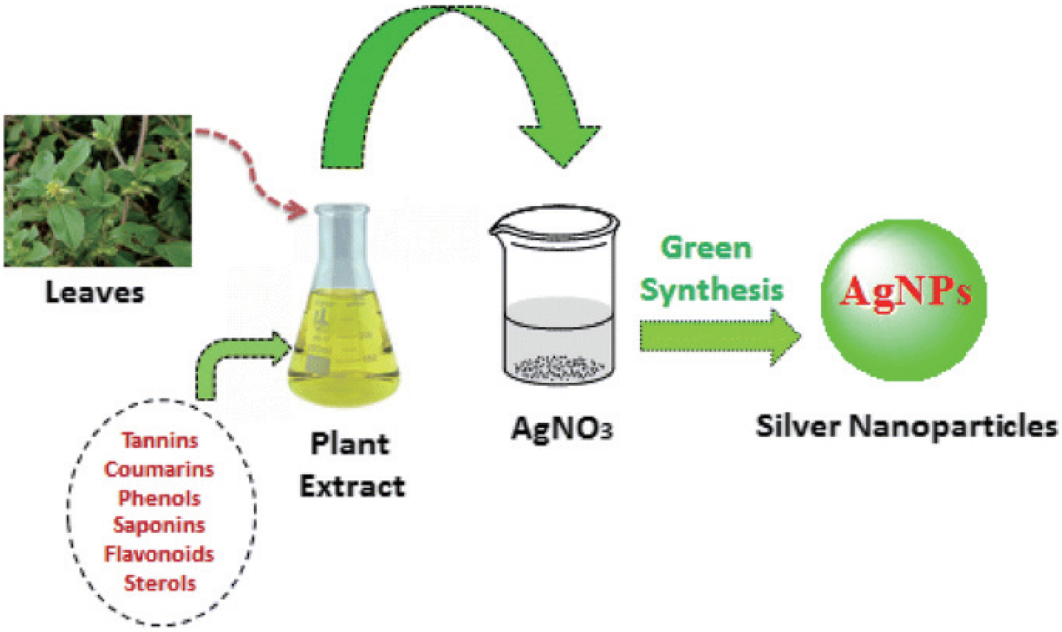

Figure 1: Diagrammatically representation of the preparation of the Green silver Nanoparticles

can enhance the synthesis efficiency and control over nanoparticle morphology. Biomolecules such as citric acid, ascorbic acid, or metal ions may act synergistically with plant extracts to facilitate nucleation and growth processes.

Plant Diversity

The rich biodiversity of plant sources offers a vast reservoir of bioactive compounds suitable for AgNP synthesis [19]. Various medicinal herbs, fruits, vegetables, and aromatic plants have been explored for their potential in nanoparticle fabrication. Each plant species imparts unique chemical constituents and functional groups to the synthesis process, influencing nanoparticle size, shape, and surface chemistry. Commonly studied plant extracts include Aloe vera, green tea, neem, turmeric, and grapefruit, among others [20].

2.2. Microbial-Mediated Synthesis

Microbial Diversity

Microorganisms including bacteria, fungi, yeasts, and algae possess inherent enzymatic machinery capable of reducing metal ions to nanoparticles. Microbial synthesis routes offer several advantages, including rapid kinetics, ambient operating conditions, and intrinsic control over nanoparticle size and morphology [21]. The choice of microbial species and strains profoundly impacts the synthesis process and nanoparticle characteristics. Bacterial species such as Escherichia coli, Bacillus subtilis, and Pseudomonas aeruginosa, as well as fungal strains like Aspergillus spp. and Candida spp., are commonly employed for AgNP synthesis [22].

Tailoring Nanoparticle Properties

Genetic manipulation, culture conditions, and substrate optimization enable precise control over the size, shape, and crystallinity of microbial-synthesized AgNPs. Modulating parameters such as pH, temperature, nutrient availability, and metal ion concentration can influence the enzymatic activity and metabolic pathways involved in nanoparticle bioreduction. Moreover, the choice of culture medium, carbon source, and growth phase of microorganisms can affect the yield and stability of synthesized AgNPs. Genetic engineering approaches offer additional avenues for enhancing nanoparticle production and tailoring nanoparticle properties through overexpression or deletion of specific genes involved in metal ion reduction pathways [23].

Co-Culture and Consortia Systems

Synergistic interactions between microbial species in co-culture or consortia systems can enhance nanoparticle synthesis efficiency and broaden the scope of nanoparticle properties. Co-cultivation of multiple microbial strains with complementary metabolic capabilities may facilitate the utilization of complex substrates, improve redox balance, and promote nanoparticle biomineralization. Consortia systems comprising bacteria, fungi, and algae offer potential synergies in terms of biomass production, substrate utilization, and metabolic diversity, thereby enabling multifunctional nanoparticle synthesis with tailored properties [24].

Applications of Green-Synthesized AgNPs

The synthesis of silver nanoparticles through green routes has unlocked a myriad of applications across diverse fields, including biomedicine, environmental remediation, catalysis, sensing, and electronics. The unique physicochemical properties of green-synthesized AgNPs, coupled with their biocompatibility, antimicrobial activity, and catalytic prowess, render them invaluable in addressing pressing societal challenges and advancing technological innovation. This section provides an overview of the multifaceted applications of green-synthesized AgNPs, highlighting their contributions to various sectors and the ongoing research endeavors aimed at harnessing their full potential [25].

Biomedical Applications

Green-synthesized AgNPs hold immense promise in biomedicine, offering solutions for antimicrobial therapy, drug delivery, imaging, biosensing, and regenerative medicine. The inherent antimicrobial properties of AgNPs enable their use as antimicrobial agents in wound dressings, surgical implants, and antibacterial coatings for medical devices. Furthermore, AgNPs serve as versatile platforms for targeted drug delivery, where surface functionalization with ligands or biomolecules enables selective binding and controlled release of therapeutic payloads at specific sites of action. The optical properties of AgNPs, including localized surface plasmon resonance (LSPR), fluorescence, and surface-enhanced Raman scattering (SERS), facilitate their application in diagnostic imaging, biosensing, and bioimaging techniques. Additionally, AgNPs exhibit potential in tissue engineering and regenerative medicine, where they promote cell adhesion, proliferation, and differentiation, thereby facilitating tissue regeneration and repair [26].

Environmental Remediation

The catalytic, adsorption, and photocatalytic properties of green-synthesized AgNPs make them effective agents for environmental remediation and pollution mitigation. AgNPs serve as catalysts for various chemical reactions, including degradation of organic pollutants, reduction of toxic heavy metals, and oxidation of environmental contaminants. Their high surface area-to-volume ratio and surface reactivity enable efficient adsorption of contaminants from air, water, and soil matrices. Furthermore, AgNPs exhibit photocatalytic activity under solar or visible light irradiation, facilitating the degradation of organic dyes, pesticides, and emerging pollutants. These properties position green-synthesized AgNPs as promising candidates for wastewater treatment, air purification, and remediation of contaminated sites [27].

Catalysis and Green Chemistry

Green-synthesized AgNPs serve as catalysts in diverse catalytic transformations, including organic synthesis, hydrogenation, oxidation, and reduction reactions. Their catalytic activity arises from the synergistic interactions between metallic silver sites and surface ligands or functional groups, which facilitate the activation of substrates and promote reaction kinetics. AgNPs exhibit excellent selectivity, stability, and recyclability in catalytic processes, offering advantages over traditional catalysts based on expensive transition metals or toxic compounds. Green chemistry principles advocate for the use of benign and renewable resources in chemical processes, aligning with the sustainable synthesis and utilization of AgNPs for eco-friendly and efficient catalytic transformations [28].

Sensing and Biosensing Applications

The optical, electrical, and surface-enhanced properties of green-synthesized AgNPs enable their integration into sensing and biosensing platforms for the detection of analytes, biomolecules, and environmental pollutants. AgNP-based sensors leverage the localized surface plasmon resonance (LSPR) phenomenon, where changes in nanoparticle size, shape, or refractive index of the surrounding medium induce shifts in the plasmon band, enabling sensitive detection of target analytes. Surface functionalization of AgNPs with specific recognition elements such as antibodies, aptamers, or molecular probes enhances selectivity and sensitivity in biosensing applications. Additionally, AgNPs serve as substrates for surface-enhanced Raman scattering (SERS), amplifying the Raman signal of analyte molecules and enabling label-free detection with high sensitivity and specificity [29].

Electronics and Optoelectronics

The conductive, optically active, and morphologically tunable properties of green-synthesized AgNPs find applications in electronics, optoelectronics, and photonics. AgNPs serve as key components in printable electronics, flexible displays, transparent conductive films, and electronic textiles, where they replace conventional metal electrodes or conductive inks. Their compatibility with solution processing techniques such as inkjet printing, spray coating, and roll-to-roll deposition enables cost-effective and scalable fabrication of electronic devices on various substrates. Furthermore, AgNP-based nanocomposites exhibit intriguing optical phenomena such as plasmon-enhanced fluorescence, surface-enhanced Raman scattering (SERS), and nonlinear optical effects, paving the way for advanced photonics and sensing applications [30].

Green synthesis techniques offer sustainable and eco-friendly pathways for the fabrication of silver nanoparticles (AgNPs), leveraging natural sources such as plant extracts and microorganisms as reducing and stabilizing agents. The inherent properties of green-synthesized AgNPs, including biocompatibility, antimicrobial activity, catalytic prowess, and optical versatility, enable diverse applications across biomedical, environmental, and industrial domains. By elucidating the mechanisms, influencing factors, and applications of green synthesis techniques for AgNPs, this section underscores the potential of sustainable nanotechnology in addressing global challenges and driving technological innovation [31]. Ongoing research endeavors aim to further optimize synthesis methodologies, tailor nanoparticle properties, and explore novel applications, thereby advancing the frontier of green-synthesized AgNPs and their integration into multifunctional materials and devices [22, 23].

3. Characterization Techniques

Characterization techniques serve as indispensable tools for comprehensively understanding the intricate properties of green-synthesized silver nanoparticles (AgNPs). These techniques, encompassing a wide array of methodologies, enable researchers to delve deep into the structural, morphological, and surface attributes of AgNPs, ultimately guiding the optimization of their properties for various applications [7].

Transmission Electron Microscopy (TEM) provides high-resolution images of individual AgNPs, offering insights into their size, shape, and distribution within a sample. TEM allows researchers to visualize the morphology of nanoparticles at the nanoscale, distinguishing between different shapes such as spherical, rod-like, or faceted structures. Additionally, TEM facilitates the quantification of nanoparticle size distribution and the assessment of aggregation or agglomeration phenomena, crucial for understanding nanoparticle behavior in complex environments [32].

Scanning Electron Microscopy (SEM) complements TEM by offering surface morphology information and three-dimensional imaging capabilities. SEM provides detailed insights into the surface topography of AgNPs, revealing features such as surface roughness, particle aggregation, and interparticle interactions. Coupled with energy-dispersive X-ray spectroscopy (EDS), SEM enables elemental analysis and mapping of nanoparticle composition, aiding in the identification of surface impurities or functional groups [4, 13].

Atomic Force Microscopy (AFM) offers topographical imaging of AgNPs with sub-nanometer resolution, providing valuable information on particle height, diameter, and surface roughness. AFM-based force spectroscopy techniques allow for the measurement of adhesive forces, mechanical properties, and interactions between nanoparticles and substrates. AFM imaging enables the visualization of individual nanoparticles immobilized on surfaces, facilitating quantitative analysis of nanoparticle size distribution and aggregation behavior [33].

X-ray Diffraction (XRD) elucidates the crystallographic structure and phase composition of green-synthesized AgNPs. XRD patterns reveal characteristic diffraction peaks corresponding to crystal planes within the nanoparticles, allowing for the determination of crystal size, lattice parameters, and crystallinity. Rietveld refinement and Scherrer equation analysis enable quantitative estimation of nanoparticle size and crystallite size based on XRD data, providing valuable insights into nanoparticle growth mechanisms and structural evolution.

Selected Area Electron Diffraction (SAED) performed in conjunction with TEM provides detailed structural information on individual AgNPs. SAED patterns offer direct evidence of crystal symmetry, lattice spacing, and orientation relationships within nanoparticles. Analysis of SAED patterns allows for the identification of crystal phases, defects, and preferred crystallographic orientations, facilitating the characterization of nanoparticle structure and phase purity.

UV-Visible Spectroscopy is employed to investigate the optical properties of green-synthesized AgNPs, particularly their surface plasmon resonance (SPR) behavior. UV-Vis spectra exhibit characteristic absorption peaks attributed to SPR, providing qualitative and quantitative information on nanoparticle concentration, size, and shape. Changes in SPR peak position, intensity, and width reflect variations in nanoparticle morphology, surface chemistry, and aggregation state, enabling monitoring of synthesis kinetics and colloidal stability [34].

Fourier-Transform Infrared Spectroscopy (FTIR) offers insights into the chemical composition and surface functionalization of green-synthesized AgNPs. FTIR spectra reveal characteristic absorption bands corresponding to functional groups present in biomolecules or surface ligands associated with nanoparticles. Analysis of FTIR spectra allows for the identification of biomolecules such as polyphenols, flavonoids, and proteins involved in nanoparticle synthesis and stabilization, as well as the detection of surface modifications or chemical interactions.

Raman Spectroscopy provides detailed information on molecular vibrations and chemical bonding in green-synthesized AgNPs. Raman spectra exhibit vibrational modes associated with nanoparticle lattice vibrations, surface functional groups, and adsorbed molecules [35]. Surface-enhanced Raman scattering (SERS) techniques leverage the plasmonic properties of AgNPs to enhance Raman signals of analyte molecules, enabling ultrasensitive detection and imaging in biosensing and biomedical applications [19].

Zeta Potential Measurement and Dynamic Light Scattering (DLS) are employed to assess the colloidal stability and surface charge of green-synthesized AgNPs in solution. Zeta potential analysis quantifies the electrokinetic potential of nanoparticles, providing information on surface charge and stability against aggregation or sedimentation [21]. DLS analysis offers insights into nanoparticle size distribution, polydispersity, and aggregation state, guiding formulation optimization and stability assessment in

Table 1: Characterization Technique of the Green silver nanoparticles [36]

Characterization Technique	Description	Applications
Transmission Electron Microscopy (TEM)	TEM utilizes a focused electron beam transmitted through a thin specimen to generate high-resolution images of individual nanoparticles.	- Morphological analysis: Determines size, shape, and distribution of nanoparticles. - Structural analysis: Provides insight into crystal structure and defects.
Scanning Electron Microscopy (SEM)	SEM scans a sample surface with a focused electron beam, producing high-resolution images that reveal surface morphology and topography.	- Surface characterization: Provides information on nanoparticle aggregation, surface roughness, and interparticle interactions. - Elemental analysis: Enables identification of elemental composition using energy-dispersive X-ray spectroscopy (EDS).
Atomic Force Microscopy (AFM)	AFM employs a sharp tip mounted on a cantilever to scan the surface of nanoparticles, measuring forces between the tip and sample.	- Surface profiling: Measures particle height, diameter, and surface roughness at the nanoscale. - Mechanical properties analysis: Investigates adhesive forces and mechanical properties of nanoparticles.
X-ray Diffraction (XRD)	XRD measures the diffraction pattern of X-rays scattered by crystalline materials, providing information on crystal structure and phase composition.	- Structural analysis: Determines crystallographic orientation, lattice parameters, and phase purity of nanoparticles. - Crystallinity determination: Evaluates the degree of crystallinity in synthesized nanoparticles.
Selected Area Electron Diffraction (SAED)	SAED captures diffraction patterns from specific regions of a sample using a transmission electron microscope (TEM), offering detailed structural information.	- Crystallographic orientation: Provides insights into lattice spacing, crystal symmetry, and preferred crystallographic orientations within nanoparticles. - Phase identification: Identifies crystal phases present in the sample based on diffraction patterns.
UV-Visible Spectroscopy	UV-Vis spectroscopy measures the absorption of electromagnetic radiation in the UV-visible range, revealing optical properties such as surface plasmon resonance (SPR).	- Quantitative analysis: Determines nanoparticle concentration, size, and shape based on SPR peaks. - Stability assessment: Monitors changes in SPR peak position and intensity to evaluate nanoparticle stability.

Fourier-Transform Infrared Spectroscopy (FTIR)	FTIR spectroscopy analyzes the absorption of infrared radiation by functional groups in nanoparticles, offering insights into surface chemistry and molecular interactions.	- Surface functionalization: Identifies biomolecules, surface ligands, and chemical moieties involved in nanoparticle synthesis and stabilization. Chemical bonding analysis: Provides information on molecular vibrations and interactions within nanoparticles.
Raman Spectroscopy	Raman spectroscopy measures the inelastic scattering of photons by molecular vibrations in nanoparticles, enabling characterization of surface chemistry and molecular structure.	- Surface characterization: Analyzes vibrational modes associated with surface functional groups, defects, and adsorbed molecules. - Chemical fingerprinting: Provides unique spectral signatures for identifying nanoparticle constituents and surface modifications.
Zeta Potential Measurement	Zeta potential measurement assesses the electrokinetic potential of nanoparticles in solution, indicating surface charge and colloidal stability.	- Colloidal stability assessment: Determines nanoparticle stability against aggregation or sedimentation based on surface charge and electrostatic interactions. - Surface modification evaluation: Monitors changes in zeta potential following surface functionalization or chemical treatment.
Dynamic Light Scattering (DLS)	DLS measures the intensity fluctuations of scattered light by nanoparticles in solution, providing information on particle size distribution and colloidal behavior.	- Particle size analysis: Evaluates nanoparticle size distribution, polydispersity, and aggregation state in solution. - Colloidal stability assessment: Tracks changes in nanoparticle size and dispersity over time to assess stability and aggregation kinetics.

nanoparticle-based formulations, **Table 1**.

4. Applications of Green-Synthesized AgNPs

Green-synthesized silver nanoparticles (AgNPs) exhibit a plethora of applications spanning various sectors, owing to their unique physicochemical properties and environmentally benign synthesis methods [7]. In the biomedical realm, AgNPs have garnered significant attention for their remarkable antimicrobial activity against a broad spectrum of pathogens, including bacteria, fungi, and viruses. Their ability to inhibit microbial growth makes them invaluable in medical settings, where they are integrated into wound dressings, surgical implants, and biomedical devices to prevent infections and promote tissue regeneration. Moreover, AgNPs are increasingly utilized in drug delivery systems, where their high surface area-to-volume ratio and tunable surface chemistry enable efficient encapsulation and controlled release of therapeutic agents. Surface-functionalized AgNPs serve as carriers for drugs, genes, and imaging agents, facilitating targeted delivery to specific tissues or cells while minimizing off-target effects and systemic toxicity. Additionally, AgNPs find application in diagnostic imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI), and photoacoustic imaging, where their unique optical properties enhance imaging contrast and sensitivity, enabling early disease detection and monitoring [37].

In the realm of environmental remediation, AgNPs offer promising solutions for water purification and air filtration [13]. Their catalytic activity enables the degradation of organic pollutants and microbial pathogens in water, making them effective agents for wastewater treatment and drinking water purification. AgNP-based nanocomposites are incorporated into filtration membranes and adsorbents to remove contaminants, heavy metals, and emerging pollutants from aqueous environments, thereby addressing pressing water quality issues. Similarly, in air filtration systems, AgNPs serve as efficient traps for airborne pollutants, including volatile organic compounds (VOCs), particulate matter, and microbial aerosols. Their antimicrobial properties mitigate the risk of airborne infections in indoor environments, promoting air quality and occupant health.

Furthermore, AgNPs play a pivotal role in catalysis and green chemistry, where they catalyze various organic transformations with high efficiency and selectivity [21]. Green synthesis routes utilizing AgNPs enable sustainable and environmentally benign synthesis of fine chemicals, pharmaceuticals, and specialty materials. AgNP-based catalysts facilitate oxidation, reduction, and carbon-carbon bond formation reactions, leading to the development of green synthetic methodologies with reduced energy consumption and minimal waste generation. Moreover, AgNPs serve as catalysts in green solvent systems, enabling the use of benign solvents and reaction conditions that align with the principles of green chemistry [36]. These sustainable catalytic processes contribute to the development of eco-friendly chemical processes and the transition towards a circular economy [38].

In sensing and biosensing applications, AgNPs play a crucial role as transducing elements in various detection platforms for analytes, biomolecules, and environmental pollutants. Surface-functionalized AgNPs are employed in biosensors and point-of-care diagnostic devices for the rapid and sensitive detection of disease biomarkers, infectious agents, and drug residues. Their unique optical, electrical, and surface-enhanced properties enable label-free detection with high specificity and sensitivity, making them valuable tools in medical diagnostics and healthcare monitoring. Additionally, AgNP-based sensors find application in environmental monitoring, food safety testing, and forensic analysis, where they enable on-site detection and real-time monitoring of target analytes in complex matrices.

In the realm of electronics and optoelectronics, AgNPs are utilized in various applications, including printed electronics, transparent conductive films, and photovoltaic devices. AgNP-based conductive inks and coatings enable the fabrication of flexible circuits, RFID tags, and wearable sensors through solution-processing techniques such as inkjet printing and roll-to-roll deposition [14. 48]. These printed electronics offer cost-effective and scalable manufacturing solutions for flexible and stretchable electronic devices on diverse substrates. Furthermore, AgNP-based transparent conductive films serve as alternatives to conventional indium tin oxide (ITO) electrodes in touchscreens, displays, and solar cells [39]. Their high conductivity, optical transparency, and flexibility enhance device performance and durability, paving the way for the development of next-generation electronic and optoelectronic technologies [8].

Additionally, AgNPs find application in food packaging and preservation, where they extend the shelf life of perishable foods and prevent microbial spoilage. Antimicrobial coatings and films containing AgNPs inhibit the growth of bacteria, fungi, and mold on food surfaces, reducing the risk of foodborne illnesses and food waste. Moreover, AgNP-based sensors embedded in food packaging materials detect changes in food quality, such as pH, temperature, and gas composition, providing real-time monitoring and quality assurance throughout the food supply chain [20].

In textiles and apparel, AgNPs impart antimicrobial, UV-protective, and self-cleaning properties to fabrics and garments, enhancing wearer comfort and hygiene. Antimicrobial textiles containing AgNPs inhibit the growth of odor-causing bacteria and fungi, reducing malodor and skin irritation in clothing, socks, and sportswear. UV-protective fabrics infused with AgNPs offer enhanced sun protection by blocking harmful ultraviolet (UV) radiation, preventing sunburn and skin damage during outdoor activities [40]. Furthermore, AgNP-coated textiles exhibit self-cleaning properties, repelling water and dirt to maintain fabric cleanliness and appearance over time.

Moreover, AgNPs find applications in energy harvesting and storage devices, where they enhance device efficiency, stability, and performance. In photovoltaic devices, AgNPs are incorporated into solar cells and dye-sensitized solar cells (DSSCs) to improve light absorption and charge transport properties. Plasmonic effects of AgNPs enhance light trapping and photon absorption in photovoltaic materials, leading to increased power conversion efficiency and energy yield. Additionally, AgNP-modified electrodes in lithium-ion batteries and supercapacitors enhance electron transfer kinetics and electrode stability, improving energy storage capacity and cycle life. Nanoparticle coatings prevent electrode degradation and dendrite formation, leading to more reliable and durable energy storage devices for renewable energy applications [38, 49].

In biotechnology and agriculture, AgNPs find application in various fields, including plant growth promotion, crop protection, and nanobiotechnology. AgNPs stimulate plant growth and enhance crop yield when applied as foliar sprays or soil amendments, promoting nutrient uptake and stress tolerance in plants. Nanoparticle-mediated delivery of agrochemicals, such as pesticides and fertilizers, enables targeted delivery and controlled release, reducing chemical leaching and environmental pollution [41]. Moreover, AgNPs serve as carriers for biomolecules, genes, and therapeutic agents in biotechnological applications, facilitating targeted delivery and controlled release in drug delivery systems, gene therapy, and tissue engineering.

Finally, in cosmetics and personal care products, AgNPs offer antimicrobial, anti-inflammatory, and antioxidant benefits for skincare and hair care formulations. AgNP-containing creams, lotions, and serums combat acne, eczema, and other skin conditions by inhibiting bacterial growth and reducing inflammation. Nanoparticles promote skin regeneration and wound healing while protecting against oxidative stress and environmental damage [42]. Furthermore, AgNP-infused shampoos and conditioners alleviate dandruff and scalp infections, promoting healthy hair growth and scalp hygiene [21]. Nanoparticle coatings on hair fibers reduce frizz and static electricity, enhancing hair manageability and appearance, **Table 2**.

The application of green-synthesized silver nanoparticles (AgNPs) in drug delivery represents a significant advancement in the field of therapeutics [5, 16]. These nanoparticles offer several advantages, including their biocompatibility, surface functionality, and tunable properties, making them ideal candidates for targeted and controlled drug delivery. One of the key advantages of AgNPs is their ability to be functionalized with targeting ligands, allowing for selective delivery of therapeutic agents to specific cells or tissues while minimizing systemic toxicity. Additionally, AgNPs enable controlled release of drugs through surface modification or encapsulation, offering tailored release profiles to optimize therapeutic efficacy. Moreover, AgNPs enhance the solubility and stability of hydrophobic drugs, improving their bioavailability and facilitating drug delivery [43]. These nanoparticles also provide a protective barrier for encapsulated drugs, prolonging their shelf-life and protecting them from degradation. Furthermore, AgNPs can be engineered to possess multifunctional properties, enabling simultaneous drug delivery and diagnostic imaging for real-time monitoring of therapeutic response. In cancer therapy, AgNP-based drug delivery systems hold significant promise for delivering chemotherapeutic agents, nucleic acid-based therapeutics, and photothermal agents to tumor sites, offering potential solutions to overcome challenges associated with conventional cancer therapies. Despite the potential of AgNPs in drug delivery, challenges remain regarding biocompatibility, long-term safety, and scalability of green synthesis methods. Future research efforts should focus on optimizing AgNP-based drug delivery systems, elucidating their pharmacokinetics and biodistribution, and conducting preclinical studies to evaluate their efficacy and safety in vivo. Overall, the application of green-synthesized AgNPs in drug delivery represents a promising approach to enhance the efficacy, safety, and precision of therapeutic interventions in various disease conditions.

5. Challenges and Future Perspectives

Navigating the future of green-synthesized silver nanoparticles (AgNPs) requires addressing several critical challenges while capitalizing on emerging opportunities [44]. Firstly, ensuring the biocompatibility and safety of AgNPs remains paramount. Comprehensive toxicity assessments are imperative to elucidate potential adverse effects on human health and the environment, thus facilitating their safe integration into biomedical and environmental applications. Moreover, standardization and quality control measures are essential to ensure the reproducibility and scalability of green synthesis methods. Streamlining synthesis protocols and implementing rigorous quality control procedures will enhance the consistency and reliability of AgNP-based formulations, accelerating their translation from the laboratory to practical applications.

Stability and aggregation present additional hurdles in the deployment of AgNPs. AgNPs are susceptible to aggregation and instability under various environmental conditions, compromising their performance and therapeutic efficacy [45]. Overcoming these challenges requires innovative strategies to enhance nanoparticle stability and prevent aggregation during storage and administration. Advanced characterization techniques, including in situ imaging and computational modeling, offer insights into the physicochemical properties and behavior of AgNPs, facilitating the design of stable and functional nanomaterials for targeted applications [46].

Biodistribution, pharmacokinetics, and environmental impact constitute significant considerations for the future of AgNPs. A deeper understanding of AgNP metabolism, tissue accumulation, and elimination pathways is crucial for predicting their efficacy and safety in drug delivery and environmental remediation [47]. Furthermore, sustainable approaches for AgNP synthesis and disposal are imperative to minimize environmental pollution and mitigate ecological risks. Adopting green synthesis methods and implementing eco-friendly disposal practices will ensure the sustainability

Table 2: List of various applications of Green silver nanoparticles

Application Area	Description
Biomedical Applications	AgNPs exhibit potent antimicrobial activity against a broad spectrum of pathogens, making them valuable for wound dressings, surgical implants, and medical devices. They also serve as drug delivery vehicles, enabling targeted delivery of therapeutic agents. Additionally, AgNPs enhance diagnostic imaging modalities, such as CT, MRI, and photoacoustic imaging, by providing contrast enhancement and improving detection sensitivity.
Environmental Remediation	AgNPs are utilized for water purification, where they catalyze the degradation of organic pollutants and microbial pathogens. They are incorporated into filtration membranes and adsorbents for wastewater treatment and drinking water purification. Additionally, AgNPs are employed in air filtration systems to trap airborne pollutants and inhibit microbial growth, promoting indoor air quality and occupant health.
Catalysis and Green Chemistry	AgNPs serve as catalysts in various organic transformations, enabling sustainable synthesis of fine chemicals and pharmaceuticals. They facilitate oxidation, reduction, and carbon-carbon bond formation reactions, leading to the development of green synthetic methodologies with reduced energy consumption and minimal waste generation. Moreover, AgNPs promote the use of benign solvents and reaction conditions, aligning with principles of green chemistry.
Sensing and Biosensing	AgNPs are integrated into biosensors and diagnostic devices for the detection of biomolecules, infectious agents, and environmental pollutants. Surface-functionalized AgNPs enable sensitive and selective detection with rapid response times. They find applications in medical diagnostics, environmental monitoring, food safety testing, and forensic analysis, offering portable and cost-effective solutions for on-site detection.
Electronics and Optoelectronics	AgNPs are utilized in printed electronics, transparent conductive films, and photovoltaic devices. They enable the fabrication of flexible circuits, RFID tags, and wearable sensors through solution-processing techniques. Moreover, AgNP-based transparent conductive films serve as alternatives to conventional ITO electrodes in touchscreens, displays, and solar cells, enhancing device performance and durability.
Food Packaging and Preservation	AgNPs extend the shelf life of perishable foods and prevent microbial spoilage when incorporated into food packaging materials. They inhibit the growth of bacteria and fungi on food surfaces, reducing the risk of foodborne illnesses and food waste. Additionally, AgNP-based sensors embedded in food packaging detect changes in food quality, providing real-time monitoring and quality assurance throughout the food supply chain.
Textiles and Apparel	AgNPs impart antimicrobial, UV-protective, and self-cleaning properties to fabrics and garments, enhancing wearer comfort and hygiene. They inhibit the growth of odor-causing bacteria and fungi in clothing, socks, and sportswear. Additionally, AgNP-coated textiles offer enhanced sun protection by blocking harmful UV radiation, promoting skin health and reducing the risk of sunburn and skin damage.
Energy Harvesting and Storage	AgNPs enhance the efficiency and stability of photovoltaic devices and energy storage systems. They improve light absorption and charge transport properties in solar cells and DSSCs, leading to increased power conversion efficiency and energy yield. Moreover, AgNP-modified electrodes in lithium-ion batteries and supercapacitors enhance electron transfer kinetics and electrode stability, improving energy storage capacity and cycle life.
Biotechnology and Agriculture	AgNPs stimulate plant growth and enhance crop yield when applied as foliar sprays or soil amendments. They serve as carriers for agrochemicals, enabling targeted delivery and controlled release of pesticides and fertilizers. Additionally, AgNPs find applications in biotechnological research, gene therapy, and tissue engineering, facilitating targeted delivery and controlled release of therapeutic agents and biomolecules.
Cosmetics and Personal Care	AgNPs offer antimicrobial, anti-inflammatory, and antioxidant benefits for skincare and hair care formulations. They combat acne, eczema, and other skin conditions by inhibiting bacterial growth and reducing inflammation. Additionally, AgNP-infused shampoos and conditioners alleviate dandruff and scalp infections, promoting healthy hair growth and scalp hygiene. Nanoparticle coatings on hair fibers reduce frizz and static electricity, enhancing hair manageability.

of AgNP-based technologies and mitigate their environmental footprint [48].

Looking ahead, advanced multifunctional nanoplatforms and smart drug delivery systems hold promise for enhancing the efficacy and precision of therapeutic interventions. By integrating AgNPs with other nanomaterials and designing stimuli-responsive nanocarriers, researchers can achieve spatiotemporal control over drug release and targeting, minimizing off-target effects and maximizing therapeutic outcomes [49]. Additionally, AgNP-based contrast agents and diagnostic probes offer opportunities for non-invasive biomedical imaging and disease diagnostics, facilitating early detection and personalized treatment strategies.

Finally, regulatory compliance and safety standards are critical for guiding the responsible development and deployment of AgNP-based products [50]. Establishing robust regulatory frameworks and safety standards will ensure the safe use of AgNPs in biomedical, environmental, and consumer applications, fostering public trust and confidence in their utility and reliability. Overall, addressing these challenges and capitalizing on emerging opportunities will unlock the full potential of green-synthesized AgNPs, driving innovation and progress in healthcare, environmental sustainability, and technological advancement [51].

6. Regulatory Guideline for the Silver Nanoparticles

Regulatory guidelines for silver nanoparticles (AgNPs) play a crucial role in ensuring their safe and responsible use across various applications. These guidelines encompass a range of considerations, starting with biocompatibility and toxicity assessments. Regulatory agencies mandate comprehensive studies to evaluate the potential adverse effects of AgNPs on human health and the environment, covering aspects such as cytotoxicity, genotoxicity, and immunotoxicity [52]. Standardized protocols from organizations like the International Organization for Standardization (ISO) and the Organization for Economic Co-operation and Development (OECD) guide these assessments, providing a framework for risk evaluation. Risk assessments inform risk management strategies, which aim to mitigate identified risks through control measures like exposure limits and occupational safety practices [53].

Furthermore, product labeling and reporting requirements are essential components of regulatory compliance. Manufacturers and distributors must provide clear and accurate labeling on AgNP-based products, detailing their composition, usage instructions, and potential hazards. Additionally, reporting requirements may necessitate the submission of data on nanoparticle characteristics, production methods, and toxicity profiles to regulatory authorities for product registration and approval. Adherence to Good Manufacturing Practices (GMP) is another critical aspect, ensuring the quality, consistency, and safety of AgNP-based products throughout the manufacturing process [54].

Environmental regulations govern the release, disposal, and environmental impact of AgNPs to mitigate potential ecological risks. Regulatory agencies establish limits on nanoparticle discharge into air, water, and soil, while environmental risk assessments inform management strategies to prevent environmental contamination [15]. Moreover, international collaboration and harmonization efforts seek to standardize regulatory guidelines and practices across different regions and jurisdictions. Organizations like the International Council on Nanotechnology (ICON) and the Nanotechnology Standards Panel (NSP) work towards developing consensus-based standards and guidelines for nanomaterials [55].

7. Conclusion

In conclusion, the proliferation of silver nanoparticles (AgNPs) in various marketed products underscores their versatility and utility across diverse industries. From healthcare to consumer goods and environmental technologies, AgNPs offer valuable properties such as antimicrobial efficacy, stability, and biocompatibility, making them integral components of numerous applications. The widespread adoption of AgNP-based products, including wound dressings, textiles, cosmetics, water filters, and medical devices, reflects their significant impact on enhancing human health, improving product performance, and promoting environmental sustainability.

However, the increasing use of AgNPs also raises important considerations regarding their safety, regulatory compliance, and environmental impact. Regulatory guidelines play a crucial role in ensuring the safe and responsible use of AgNPs, guiding manufacturers in product development, labeling, and risk assessment. Continued research efforts are essential to address emerging challenges, such as biocompatibility assessment, standardization of synthesis methods, and environmental risk mitigation,

Table 3: List of Marketed Products available with Silver Nanoparticles

Product Type	Description
Antimicrobial Wound Dressings	Wound dressings infused with silver nanoparticles to prevent infections and promote wound healing.
Antibacterial Textiles	Fabrics and textiles treated with silver nanoparticles to inhibit the growth of odor-causing bacteria and maintain freshness.
Cosmetics and Personal Care	Cosmetics, creams, lotions, soaps, and toothpaste containing silver nanoparticles for their antimicrobial and skin-soothing properties.
Water Purification Filters	Water filters incorporating silver nanoparticles to remove contaminants and inhibit microbial growth, improving drinking water quality.
Food Packaging Materials	Films and coatings containing silver nanoparticles used in food packaging to extend the shelf life of perishable foods by reducing microbial growth.
Medical Devices	Catheters, implants, and surgical instruments incorporating silver nanoparticles for antimicrobial properties, reducing the risk of infections.
Topical Antimicrobial Sprays/Gels	Sprays and gels for topical application containing silver nanoparticles to prevent infections and support wound healing on minor cuts and abrasions.
Air Purification Systems	Air filters and coatings with silver nanoparticles used in air purification systems to remove airborne pollutants and inhibit microbial growth, enhancing indoor air quality.
Sunscreen and UV-Protective Clothing	Sunscreens and clothing items infused with silver nanoparticles to enhance UV protection and prevent sun damage to the skin.
Household Cleaning Products	Surface disinfectants, antimicrobial sprays, and cleaning solutions containing silver nanoparticles to kill bacteria and microorganisms on household surfaces.

while advancing the understanding of AgNP behavior and interactions in complex biological and environmental systems.

Overall, the continued innovation and collaboration in the field of silver nanoparticles hold promise for unlocking new opportunities and addressing societal needs in healthcare, consumer products, and environmental sustainability. By navigating the complexities of safety, regulation, and sustainability, stakeholders can harness the full potential of AgNPs to drive positive impact and meet the evolving demands of a rapidly changing world.

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Author contribution

All authors contributed to the idea and design of the review, with drafting of the article, and revision of the article.

Conflicts of interest

The authors declare that there is no conflict of interest.

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