World Journal of Pharmaceutical Science and Research
www.wjpsronline.com

Review Article

ISSN: 2583-6579
SJIF Impact Factor: 6.916
Year - 2026
Volume: 5; Issue: 6
Page: 297-310

EMERGING TRENDS IN THE SYNTHESIS AND THERAPEUTIC EVALUATION OF SILVER NANOPARTICLES

Avijit Bej*[1], Rakesh Kumar Sahu*[2], Ravindra Kumar[3], Aniked Kumar[4], Abhay Kumar Singh[5], Haroon Rashid[6], Niraj Kumar[7]

[1,2]Assistant Professor, Mahadeva Lal Schroff College of Pharmacy Aurangabad Bihar-824102.
[3-7]B. Pharm Final Year Students, Mahadeva Lal Schroff College of Pharmacy Aurangabad Bihar-824102.

Article Received: 14 April 2026 || Article Revised: 05 May 2026 || Article Accepted: 25 May 2026

***Corresponding Author: Avijit Bej, Rakesh Kumar Sahu**
Assistant Professor, Mahadeva Lal Schroff College of Pharmacy Aurangabad Bihar-824102.

DOI: https://doi.org/10.5281/zenodo.20444421

How to cite this Article: Avijit Bej, Rakesh Kumar Sahu, Ravindra Kumar, Aniked Kumar, Abhay Kumar Singh, Haroon Rashid, Niraj Kumar (2026) EMERGING TRENDS IN THE SYNTHESIS AND THERAPEUTIC EVALUATION OF SILVER NANOPARTICLES. World Journal of Pharmaceutical Science and Research, 5(6), 297-310.

ABSTRACT

Silver nanoparticles (AgNPs) have emerged as highly versatile agents in biomedical science due to their unique physicochemical properties, including a high surface-area-to-volume ratio and strong surface plasmon resonance. This review highlights recent advancements in the synthesis of AgNPs, emphasizing the crucial role of tailoring size typically between 1 and 100 nm—and diverse morphologies such as nanorods and nanoprisms to optimize localized surface plasmon resonance (LSPR). We examine the significant shift toward "green" synthesis methods utilizing extracts from plants, fungi, and bacteria, which serve as natural reducing and stabilizing agents to produce nanoparticles with enhanced biocompatibility and lower toxicity than traditional chemical routes. The review further evaluates the extensive therapeutic applications of AgNPs, focusing on their multi-directional antimicrobial mechanisms, such as DNA damage, protein disruption, and the induction of reactive oxygen species (ROS), which enable them to combat multi-drug-resistant pathogens and various viruses, including SARS-CoV-2. Beyond infection control, the integration of AgNPs into hydrogels and scaffolds demonstrates substantial efficacy in promoting keratinocyte proliferation for wound healing and stimulating osteoblast activity for bone regeneration. Additionally, we explore emerging roles in oncology through antiangiogenic and pro-apoptotic effects, and in metabolic health via the inhibition of glucose-regulating enzymes like alpha-amylase. Despite these promising trajectories, the review concludes by addressing critical challenges, including potential systemic toxicity and the need for rigorous regulatory frameworks to manage the environmental and biological impact of long-term silver accumulation.

KEYWORDS: Silver nanoparticles, Biomedical Applications, Antimicrobial, Toxicity.

INTRODUCTION

The clinical utilization of silver ions boasts a rich historical legacy, particularly as a foundational treatment for burns and traumatic wounds. Due to their potent antimicrobial characteristics, these ions have remained a focal point of scientific inquiry, sparking broad research aimed at commercializing silver-based medical products. While traditional applications provided a baseline for efficacy, the emergence of nanotechnology has fundamentally transformed and optimized the delivery of silver.

Silver nanoparticles (AgNPs) represent a sophisticated advancement in this field, consisting of clusters of elemental silver atoms organized into a precise nanostructure. These particles act as dynamic reservoirs that release silver ions via oxidative processes, a mechanism that underpins their versatility across multiple biological domains. AgNPs are increasingly recognized for their multifaceted biological benefits, demonstrating not only antibacterial prowess but also significant anti-inflammatory and antiviral capabilities.[1]

The therapeutic performance of AgNPs is intrinsically linked to their specialized physicochemical attributes, including their surface charge, morphology, and high surface-area-to-volume ratio. A defining characteristic of these particles is their localized surface plasmon resonance (LSPR), a physical phenomenon that dictates their unique optical properties. Typically ranging from 1 to 100 nm in size, AgNPs exhibit varied functional behaviors depending on their dimensions. This size-dependency is especially critical in high-precision fields such as biosensing and medical imaging, where LSPR-driven optical traits determine the overall sensitivity and effectiveness of the nanoparticle.[2]

Beyond size, the morphology of silver nanoparticles (AgNPs) is highly varied, with the specific shape being determined by synthesis variables such as reagent concentration, pH, and temperature. These methods can produce diverse structures, including nanospheres, nanorods, nanocubes, nanowires, and nanoprisms, each possessing distinct physical properties that dictate their specific functional roles. For instance, triangular AgNPs are exceptionally effective in antimicrobial applications because their sharp edges and vertices facilitate more intense interactions with and disruption of bacterial cell membranes. Consequently, the versatility of AgNPs allows them to be utilized across a broad spectrum of industries, ranging from the development of high-sensitivity biosensors and anticancer treatments to the enhancement of food packaging and the promotion of wound healing.[3]

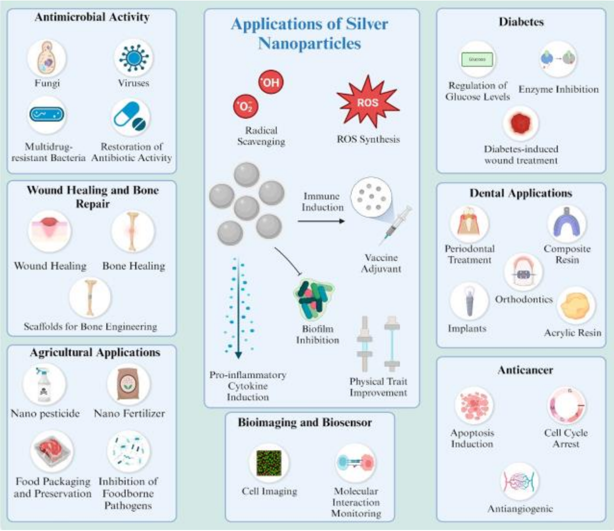

Figure 1: Applications of silver NPs.

This review examines the primary functional domains of silver nanoparticles (AgNPs) within the biomedical sector, identifying their potent antimicrobial properties as the foundational element of their clinical utility. In agricultural contexts, these particles are utilized to suppress microbial proliferation for food preservation and to mitigate the impact of plant pathogens, while simultaneously improving the physical characteristics of food packaging and stimulating plant growth factors.[4] This reliance on antibacterial and antibiofilm performance extends to dentistry and wound management, where AgNPs are applied in precise concentrations to regulate oral and dermal microenvironments, often leading to enhanced therapeutic outcomes. Beyond infection control, AgNPs exhibit specialized efficacy in the treatment of chronic conditions like cancer and diabetes, while their structural functionalization remains a critical factor for advancements in biosensing and bioimaging technologies. Current bibliographic trends indicate a high volume of scholarly output regarding silver nanoparticles, with publication rates reaching a steady plateau that is expected to persist through late 2024. An analysis of these publications confirms that antimicrobial studies dominate the current literature, followed closely by research into agricultural and oncological applications, while dental and wound healing studies occupy a smaller, yet significant, portion of the global research distribution.[5]

Silver nanoparticles (AgNPs) continue to show immense potential in addressing antibiotic resistance and advancing oncological treatments through their specialized cytotoxic properties. In the realm of wound management, these particles foster tissue repair while simultaneously preventing localized infections, marking a significant step forward in therapeutic care. Furthermore, their distinct magnetic and surface plasmon resonance (SPR) characteristics make them indispensable for early disease detection via high-precision bioimaging and diagnostic sensing. This review explores these established applications while specifically highlighting emerging research in bone regeneration and diabetes management.

A critical component of this study is the evaluation of the safety and regulatory landscape surrounding AgNPs, which is necessary for their eventual integration into clinical environments. By synthesizing current trends across diverse sectors—including dentistry, agriculture, and cancer therapy—this research underscores a future driven by interdisciplinary innovation and sustainable synthesis methods.[6] Despite their extensive history, interest in AgNPs remains high, as evidenced by steady publication rates and the ongoing need for advanced nanotechnological solutions. Consequently, the continued exploration of AgNPs is vital for guiding the future of nanomedicine while carefully weighing their environmental and ethical consequences.

Table 1: Summary of the Biomedical and Industrial Applications of Silver Nanoparticles (AgNPs).

Application Area	**Primary Functional Roles**	**Key Advantages & Characteristics**
Antimicrobial & Antiviral	Fighting drug-resistant bacteria and various viruses	Uses multiple mechanisms like DNA damage and oxidative stress to kill pathogens
Oncology	Acting as targeted anticancer agents	Induces cancer cell death and prevents the growth of new tumor blood vessels
Wound Healing	Speeding up skin repair and preventing infection	Boosts skin cell growth and reduces inflammation at the wound site
Diagnostics	Powering bioimaging and high-sensitivity sensors	Uses unique optical and magnetic traits for early disease detection
Bone Regeneration	Strengthening bone repair materials	Stimulates bone-building cells and improves the physical strength of implants
Diabetes Research	Controlling blood sugar levels	Blocks specific enzymes responsible for breaking down carbohydrates
Agriculture & Food	Pesticide management and food preservation	Keeps food fresh longer and protects plants from microbial diseases
Research & Safety	Managing safety risks and regulations	Focuses on sustainable production and safe clinical use

Antibacterial Activity and Antibiotic Resistance

Silver has a storied history as an antimicrobial agent, having been utilized for various sanitizing purposes over many centuries. With the maturation of nanotechnology, silver has transitioned into a cornerstone material within the field, primarily due to the sophisticated, multi-pronged attack strategies silver nanoparticles (AgNPs) employ against pathogens. These diverse mechanisms include the elevation of reactive oxygen species (ROS) to damage cellular DNA and proteins, the physical accumulation of particles to compromise membrane integrity, and the active disruption of established antibiotic resistance pathways.[7] The structural configuration of AgNPs serves as a vital physicochemical factor in these interactions; for example, smaller, plate-like nanoparticles offer a superior surface area that facilitates the rapid and effective release of silver ions. To maintain this high rate of ion liberation, effective surface stabilization is necessary to prevent particle aggregation, which would otherwise diminish the available surface area and reduce overall antibacterial potency.

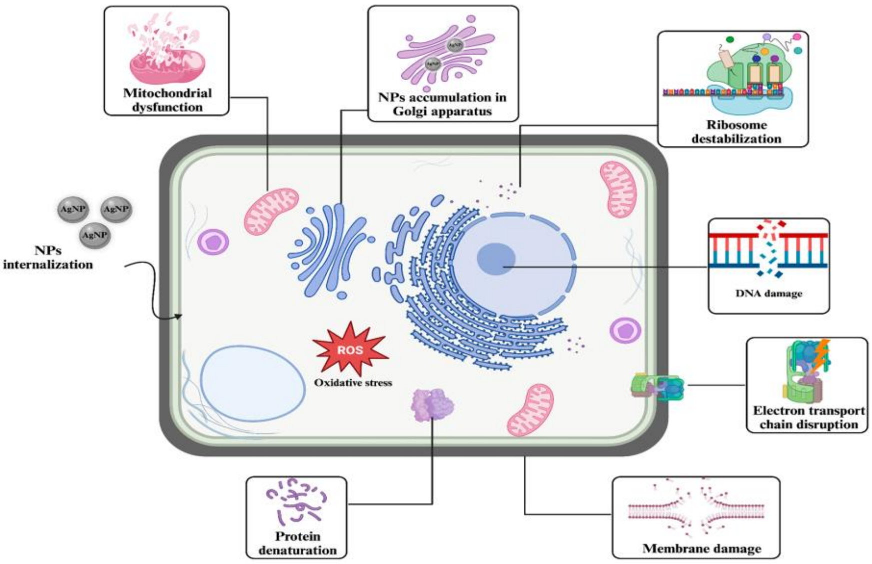

Figure 2: Antibacterial mechanisms of silver NPs.

In a comparative assessment, four distinct morphologies of silver nanoparticles—spherical, rod-shaped, triangular, and hexagonal—were evaluated for their efficacy against a range of Gram-positive and Gram-negative bacterial strains. By monitoring zones of inhibition and minimum inhibitory concentration (MIC) values across different dosages, researchers identified significant performance variations based on shape.

At specific concentrations of 242 and 249 µg/mL, spherical AgNPs produced the most expansive inhibition zones while requiring a lower concentration to achieve these results compared to the alternative structures. Furthermore, nanospheres exhibited the lowest MIC values, demonstrating superior potency, although the margin of difference between the four shapes was relatively narrow. These results correlate directly with the rate of ion liberation; the study found that spherical nanoparticles yielded the highest silver ion release at 34 µg/mL, followed by nanorods at 32 µg/mL and triangular particles at 26 µg/mL. Conversely, hexagonal AgNPs demonstrated the lowest ion release at 15 µg/mL, underscoring the critical role that particle geometry plays in driving antimicrobial performance.

Research frequently explores how the geometric structure of silver nanoparticles (AgNPs) dictates their effectiveness against bacteria.[8] Comparative studies involving nanocubes, nanospheres, and nanowires have revealed that spherical and cubic forms tend to outperform nanowires, a result largely attributed to their superior specific surface areas. In other instances, dendritic morphologies have shown even greater antibacterial potency than traditional spherical particles. These findings reinforce the principle that the physicochemical characteristics of AgNPs specifically those that maximize surface area and facilitate the efficient liberation of silver ions—are the primary drivers of successful antibacterial outcomes.

The scope of AgNP research extends beyond simple bactericidal effects to include robust performance against resilient biofilms. Modern methodologies are increasingly prioritizing "green" synthesis, utilizing biological agents such as leaf extracts, algae, fungi, and bacteria to produce nanoparticles for antibacterial testing. Given the vast volume of literature in this field, contemporary focus has shifted toward addressing more complex challenges, specifically the use of AgNPs against multi-drug-resistant (MDR) bacteria and their synergistic potential when paired with conventional antibiotics.[9]

By evaluating how these nanoparticles can enhance the performance of existing drugs, researchers are finding new ways to overcome bacterial defenses, as summarized in the recent data presented in Table 1.

Silver nanoparticles (AgNPs) have become a primary focus in the struggle against antibiotic-resistant pathogens, serving as both standalone agents and antibiotic enhancers. The proliferation of multi-drug-resistant (MDR) biofilms is often accelerated by the improper or excessive administration of traditional antibiotics, which allows resistant strains to thrive and disseminate genetic resistance within microbial communities. AgNPs provide a critical alternative by offering a distinct mode of antibacterial action that reduces the necessary dosage of conventional drugs while simultaneously hindering the development of new resistance.

The efficacy of AgNPs is particularly evident in their performance against highly resilient strains. For example, research utilizing green-synthesized AgNPs against Enterococcus faecalis, Pseudomonas aeruginosa, and Acinetobacter baumannii demonstrated that these nanoparticles remain effective even when traditional antibiotics fail. In controlled trials, while antibiotic-resistant strains showed virtually no response to standard drug controls, they exhibited significant zones of inhibition when exposed to AgNPs. Specifically, resistant E. faecalis displayed inhibition zones nearly identical to its non-resistant counterpart (approximately 12 mm), and resistant A. baumannii actually showed a slightly higher sensitivity to the nanoparticles than the non-resistant strain.[10,11]

These inhibitory effects typically become pronounced at concentrations starting from 45 µg/mL and reach their peak at around 360 µg/mL. Furthermore, minimum bactericidal concentration (MBC) and minimum inhibitory concentration (MIC) assays confirm that AgNPs maintain consistent potency across diverse bacterial groups, often achieving total bacterial clearance at concentrations as low as 22.5 µg/mL. These findings suggest that the antibacterial mechanism of AgNPs operates independently of the biological pathways typically associated with antibiotic resistance, making them invaluable tools for modern medicine.

While the fundamental efficacy of silver nanoparticles (AgNPs) as antibacterial agents is well-documented and scientifically established, the current research landscape is moving beyond simple validation toward understanding complex biological interactions. To fully realize their potential as primary candidates for overcoming antibiotic resistance, it is necessary to move away from general bactericidal testing and focus on the specific ways these particles interface with bacterial mechanisms and existing pharmacological drugs.[12] This shift in focus is critical for developing more efficient treatments that can neutralize multi-drug-resistant (MDR) strains and prevent the formation of resilient biofilms.

The following tables summarize the evolution of AgNP research priorities and the specific ways they interact with bacterial systems.

Table 2: Strategic Evolution in Silver Nanoparticle Research.

From: Established General Knowledge	**To: Emerging Priority Research Areas**
Confirming broad-spectrum antibacterial activity	Evaluating specific interference with bacterial resistance pathways
Measuring standard zones of inhibition and MIC values	Analyzing synergistic interactions when combined with conventional antibiotics
Testing efficacy against single-strain planktonic bacteria	Investigating the disruption of complex, multi-strain biofilms
Validating chemical synthesis and stability	Developing green synthesis methods to improve biocompatibility for clinical use

Table 3: Interaction Dynamics of AgNPs with Biological and Chemical Systems.

Interaction Target	**Mechanism of Action**	**Intended Therapeutic Impact**
Bacterial Resistance Mechanisms	Interferes with the specific biological pathways that bacteria use to evade drugs	Significantly lowers or halts the buildup of new antibiotic resistance
Conventional Antibiotics	Functions in tandem with existing drugs to enhance their penetration and efficacy	Reduces the required dosage of antibiotics, decreasing systemic side effects
Cellular Biofilms	Inhibits microbial attachment and proliferation in localized areas like wounds or dental cavities	Controls persistent infections that standard treatments cannot penetrate
Pathogen Defense Systems	Induces oxidative stress and physical membrane damage via silver ion release	Provides a multi-directional attack strategy that is difficult for bacteria to adapt to

Antiviral Applications

Silver nanoparticles (AgNPs) demonstrate robust antiviral capabilities through a variety of intracellular and extracellular pathways. The efficacy of these mechanisms is heavily influenced by the physicochemical properties of the nanoparticles, particularly their size. Research involving feline calicivirus (FCV) has shown that 10 nm AgNPs are significantly more effective than larger variants (75 nm or 100 nm), achieving a substantial 6.5 $\log_{10}$ reduction in viral titer. Furthermore, AgNPs can be functionalized with specific coatings to target high-profile viruses such as HIV-1, hepatitis B, and herpes simplex virus type 1.

In studies focusing on respiratory syncytial virus, AgNPs exhibited dose-dependent activity; a concentration of 50 µg/mL resulted in a 79% reduction in viral replication in vitro. Parallel in vivo experiments confirmed this efficacy, showing up to a 55% decrease in viral copy numbers at a dosage of 4 mg/kg, while simultaneously modulating the immune response by reducing pro-inflammatory cytokines and maintaining proper neutrophil recruitment.[13]

AgNPs have also been investigated as potential treatments for SARS-CoV-2. Both colloidal silver and polyvinylpyrrolidone-capped AgNPs effectively reduced viral RNA levels and prevented cell death, with the highest efficiency observed in particles sized between 2 and 15 nm. The timing of treatment appears crucial; the most significant viral reduction occurs when AgNPs are introduced simultaneously with the virus, suggesting strong extracellular interaction alongside intracellular inhibition. While the exact molecular interactions are still being studied, it is believed that AgNPs may bind directly to the virus or block cellular receptors like ACE-2, mirroring their multi-pronged antibacterial strategies to disrupt viral life cycles.[14]

Table 4: Summary of AgNP Antiviral Performance and Mechanisms.

Target Virus	Size/Concentration	Key Findings & Mechanisms
Feline Calicivirus (FCV)	10 nm	Achieved 6.5 $\log_{10}$ reduction; smaller size proved superior to 75–100 nm particles.
Respiratory Syncytial Virus	50 µg/mL (In vitro) / 4 mg/kg (In vivo)	Reduced replication by 79% and viral copies by 55%; lowered inflammatory cytokine levels.
SARS-CoV-2	2–15 nm	Inhibited viral RNA copies and prevented cell death; likely targets ACE-2 receptors or binds viral molecules.
HIV-1 & Hepatitis B	Various coatings	Surface functionalization allows for targeted inhibition of specific viral types.

Silver nanoparticles (AgNPs) utilize a consistent set of mechanisms to exert their antiviral and antifungal effects, largely governed by their size and surface characteristics. These particles disrupt viral infectivity and modulate cytokine levels in a wide range of pathogens, including human immunodeficiency virus type 1, herpes simplex virus type 2, and human parainfluenza virus type 3. The same physicochemical principles apply to antifungal research, where smaller nanoparticles frequently demonstrate superior efficacy compared to larger counterparts by facilitating more intimate contact with fungal cell walls.[15]

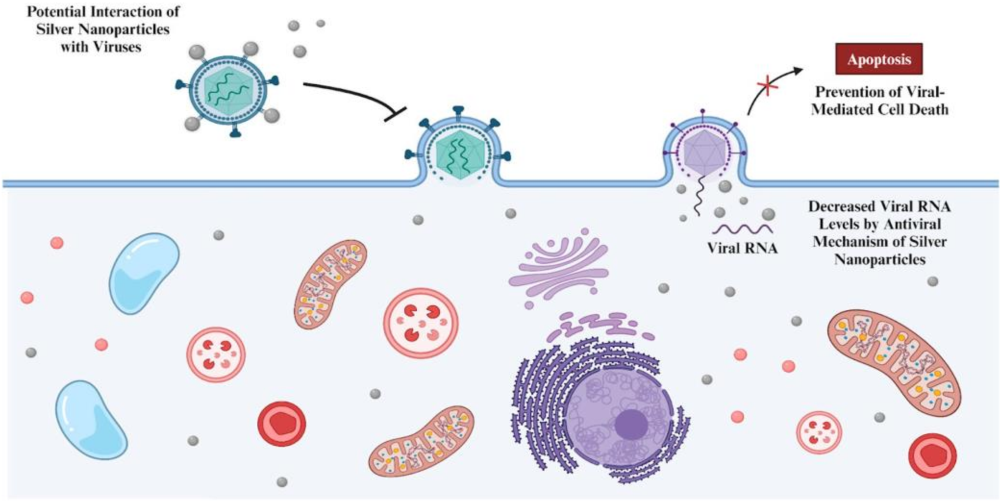

Figure 3: Antiviral mechanisms of silver NPs.

Current review reflects a high volume of research dedicated to optimizing these antimicrobial properties. Rather than merely confirming that AgNPs work, contemporary studies emphasize the comparison of variables such as the synthesis source, particle dimensions, surface functionalization, and dosage levels to maximize performance. This foundational antimicrobial capability is not a standalone field; it serves as a critical component that enhances the functionality of AgNPs in diverse sectors, including agriculture, wound healing, and dentistry.[16]

Table 5: Factors Influencing AgNP Antimicrobial Performance.

Parameter	Impact on Antimicrobial Activity	Target Pathogens
Particle Size	Smaller sizes (e.g., <15 nm) provide higher surface-to-volume ratios for faster ion release.	Bacteria, Viruses (e.g., FCV, SARS-CoV-2), and Fungi
Surface Properties	Capping agents and surface charges influence how particles attach to cellular or viral membranes.	Enveloped viruses (e.g., HIV-1, HSV-2) and drug-resistant bacteria
Concentration	Higher dosages often correlate with increased reactive oxygen species (ROS) production.	Multidrug-resistant strains and persistent biofilms
Morphology	Specific shapes (e.g., nanospheres or plates) affect the rate of silver ion liberation.	Gram-positive/negative bacteria and various fungal species

Research explored the efficacy of silver nanoparticle (AgNP)-based wound dressings using 3D fibroblast cultures. While the study noted a negative impact on mitochondrial activity after three days, there was no evidence of nuclear damage or fragmentation. Interestingly, the number of live cells within the dermal-like tissue actually increased, leading researchers to hypothesize that the reduction in mitochondrial function occurred independently of cell death or general cytotoxicity. Analysis of the dressing revealed that 94% of the silver ions remained within the material rather than leaching excessively into the biological environment.[17]

The study was further validated through an in vivo case study where a patient's wound was treated with the AgNP dressing. By day 17, the wound had completely healed, and optical microscopy confirmed the restoration of the epidermal tissue structure. High-resolution transmission electron microscopy (TEM) showed that the AgNPs were confined to the cytoplasm and absent from the cell nuclei. The authors suggested that mitochondria might increase in number and reposition themselves around the nucleus to serve as a protective barrier against the nanoparticles.

Ultimately, these results indicate that long-term use of AgNP dressings can effectively support tissue regeneration and fibroblast proliferation without posing significant toxicological risks.[18,19]

Table 6: Effects of AgNP Dressings on Tissue and Cellular Components.

Observed Component	Impact of AgNP Dressing	Key Finding
Fibroblast Cells	Increased proliferation	Wound healing progressed without interference.
Mitochondria	Decreased activity	Activity decline was not linked to cell death.
Cell Nucleus	No damage or fragmentation	No silver nanoparticles were found inside the nucleus.
Tissue Structure	Full restoration	Epidermal repair was completed by day 17.
Silver Ion Release	Minimal migration	94% of silver ions were retained within the dressing.

Because silver nanoparticles (AgNPs) effectively regulate the recovery process without obstructing natural repair, they are frequently integrated into hydrogels to boost wound healing performance. For example, research involving a PF127 polymer hydrogel loaded with AgNPs demonstrated significant antibacterial effects and concentration-dependent antioxidant activity, with radical scavenging reaching up to 65.17%. In animal models, this hydrogel caused no irritation and dramatically outperformed control groups; by the tenth day, wounds treated with a 1.0 mg concentration reached a 94.54% healing rate compared to just 60.12% in untreated subjects.[20]

Similarly, hydrogel composites stabilized with guar gum and curcumin have shown that AgNPs can enhance fibroblast proliferation by 45% and collagen production by 50% without inducing cytotoxicity at low concentrations. In comparative trials, these specialized hydrogels achieved a 73% healing rate—far exceeding the 51% recorded for commercial antibacterial gels—and accelerated the repair process by 40%. Further analysis through histopathology and gene expression revealed that AgNP-based treatments shorten the inflammatory phase by reducing interleukin-6 levels while simultaneously increasing the expression of epidermal growth factors.[21] These findings highlight AgNPs as premier candidates for advanced wound care, capable of managing infections while precisely modulating the cellular environment to speed up recovery.[22]

Table 7: Comparative Performance of AgNP-Loaded Hydrogels in Wound Care.

Treatment Type	Key Biological Impact	Performance Metric
AgNP PF127 Hydrogel	Provides high radical scavenging activity (up to 65.17%).	Achieved 94.54% healing by day 10 at 1.0 mg dosage.
Curcumin-AgNP Composite	Boosts collagen production by 50%	Repaired wounds 40% faster than

	and fibroblast growth by 45%.	standard control groups.
Commercial Antibacterial Gel	Standard infection control.	Reached only 51% healing compared to 73% for AgNP hydrogel.
Gene Expression Modulation	Lowers Interleukin-6 and raises Epidermal Growth Factor levels.	Results in a significantly shortened inflammatory phase.

Table 8: Advantages of AgNPs in Tissue Regeneration.

Feature	Mechanism of Action	Benefit to Patient
Antibacterial Potency	Exhibits 60% higher activity than many commercial alternatives.	Prevents localized infection and reduces treatment failure.
Cellular Compatibility	Maintains cell viability at concentrations below 0.100 nM.	Supports tissue growth without causing skin irritation or toxicity.
Migration Enhancement	Encourages faster cell migration to close wound gaps.	Minimizes the time a wound remains open and vulnerable.
Antioxidant Support	Regulates the environment through radical scavenging.	Protects regenerating tissue from oxidative stress.

Vaccine Adjuvant Applications

Due to their ability to trigger the release of pro-inflammatory cytokines, spark inflammatory reactions, and mobilize specific immune cells, silver nanoparticles (AgNPs) are being explored as a viable alternative for vaccine adjuvants. The primary role of an adjuvant is to amplify the body's immune response to a specific antigen, thereby enhancing the overall effectiveness of the immunization process. A growing body of research, spanning both in vitro and in vivo models, consistently demonstrates that incorporating silver NPs as an adjuvant results in a significantly heightened immune response.[23,24]

Table 9: Silver Nanoparticles as Vaccine Adjuvants.

Functional Role	Mechanism of Action	Intended Outcome
Immune Stimulation	Triggers pro-inflammatory cytokine release and inflammatory responses	Stronger recognition of the vaccine antigen
Cellular Recruitment	Mobilizes and recruits specific immune cells to the site	Enhanced systemic immunity and memory
Efficacy Improvement	Acts as a potent delivery or signaling adjuvant	Higher immunization success rates in various models

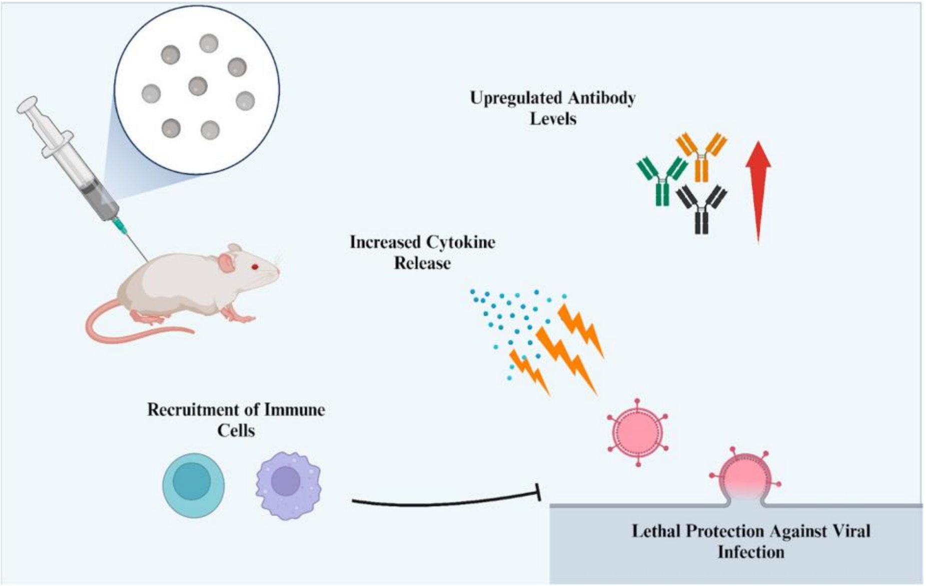

Figure 4: Usage of silver NPs as vaccine adjuvant for viral infections.

Anticancer Applications

The use of silver nanoparticles (AgNPs) in oncology represents one of the most thoroughly investigated subjects in modern nanotechnology. These nanoparticles facilitate cancer cell death through several sophisticated pathways, primarily by triggering apoptosis via mitochondrial impairment and disrupting the equilibrium of apoptotic proteins.

Beyond biochemical signaling, AgNPs can inflict direct structural and functional damage on cellular components, further driving programmed cell death. Research also suggests that AgNPs can interrupt the cancer cell cycle, specifically causing arrest in the sub-G1 phase.[25,26]

The versatility of AgNPs is frequently expanded through green synthesis—using plants with inherent medicinal properties—and by pairing them with traditional chemotherapeutic agents to boost efficacy. These bio-synthesized AgNPs often induce apoptosis by elevating reactive oxygen species (ROS) levels, upregulating the p53 tumor-suppressor gene, and activating caspase-3. For the past several years, these pathways have been the focal point of anticancer studies, with many researchers documenting ROS-mediated cell death alongside visible morphological changes and altered protein expression in apoptotic cells. Additionally, some investigations have highlighted the potential of AgNPs to inhibit angiogenesis, further restricting tumor growth.[27]

Table 10: Primary Mechanisms of AgNP Anticancer Activity.

Mechanism	Biological Impact	Resulting Effect
Mitochondrial Disruption	Destabilizes mitochondria and apoptotic protein levels	Induction of apoptosis
Cell Cycle Interference	Targets specific phases of cell division	Sub-G1 phase arrest
Oxidative Stress	Increases levels of Reactive Oxygen Species (ROS)	ROS-mediated cell death
Genetic Modulation	Upregulates tumor-suppressor genes like p53	Programmed cell death induction
Enzymatic Activation	Stimulates the activation of caspase-3	Apoptotic pathway completion
Antiangiogenic Action	Interferes with the formation of new blood vessels	Inhibition of tumor nutrient supply

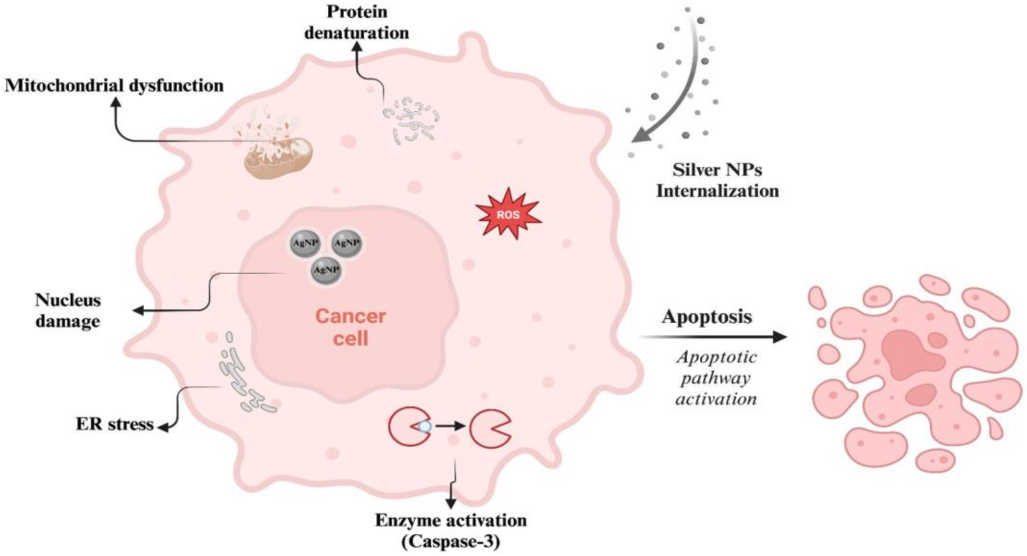

Figure 5: Anticancer mechanism of silver NPs.

The inherent toxicity of silver nanoparticles (AgNPs) and their released silver ions offers significant therapeutic promise in oncology by halting cell proliferation, triggering DNA damage, inducing oxidative stress, and compromising the integrity of cellular membranes. The physical characteristics of these nanoparticles are critical, as they dictate how effectively the particles are taken up by cells and the rate at which they release ions to initiate anticancer pathways. Consequently, precise control over the properties of AgNPs during the synthesis process is vital to calibrate the toxicity levels required for specific medical applications.[28,29]

Biosensor and Bioimaging Applications

The unique optical characteristics of silver nanoparticles (AgNPs) make them highly effective for bioimaging and biosensing technologies. Due to their surface modifiability and plasmon resonance, these particles are capable of imaging tumor cells, DNA, and specific proteins.[30] When AgNPs are conjugated with probes, they demonstrate high sensitivity for identifying antibodies and genetic material within various sensor platforms. Their utility in biosensing is further supported by their superior refractive index, sharp spectral bands, and efficient Localized Surface Plasmon Resonance (LSPR) excitation.[31]

A nanoparticle's physical dimensions and shape—including rods, bars, and triangles—significantly dictate its LSPR properties and performance in Surface-Enhanced Raman Scattering (SERS) sensors. There is a direct correlation between particle size and LSPR peak positions; specifically, as size increases, a red-shift in peaks occurs. For example, when AgNPs were used to image neural stem cells and rat leukemia cells, increasing the particle diameter from 9 nm to 32 nm resulted in a red shift for both resonance extinction and photoluminescence emission.[32]

Size also plays a critical role in detection sensitivity. In humidity sensors utilizing polyaniline–silver nanocomposites, 15 nm AgNPs outperformed 30 nm particles, providing higher sensitivity across a broad range of 5% to 95% relative humidity. This performance boost is linked to LSPR behavior, as the 15 nm particles displayed lower absorption peaks at 400 nm compared to the 420 nm peaks observed in the larger 30 nm particles.

Table 11: Optical and Sensing Performance of AgNPs.

Application Area	Key Property Utilized	Biological/Physical Target
Bioimaging	Plasmon resonance & surface modifiability	Tumor cells, DNA, and proteins
Biosensing	High sensitivity & LSPR excitation	Antibodies and various biomolecules
SERS Sensors	Geometric diversity (triangles, rods, etc.)	Molecular detection up to 100 nm scale
Environmental Sensing	Refractive index & absorption peak shifts	Wide-range humidity detection (5–95%)

Silver nanoparticles (AgNPs) are highly versatile for use in various biosensing and bioimaging platforms. Their compact dimensions and established capacity for penetrating cellular membranes make them an ideal choice for these technologies. Most notably, the ability to modify the surface of AgNPs significantly expands their functional range. By attaching specific cell-targeting biomolecules, researchers can achieve superior imaging quality and more effectively track molecular interactions.[33,34]

Table 12: Advantages of AgNPs in Imaging and Sensing.

Feature	Functional Benefit	Practical Application
Miniature Size	Facilitates easy entry into biological cells	Intracellular imaging and monitoring
Surface Modifiability	Allows for the attachment of diverse functional groups	Targeted delivery and specialized biosensors
Targeting Ability	Increases specificity for particular	Enhanced visualization of tumor cells

	biomarkers	and proteins
Molecular Monitoring	Enables observation of real-time cellular activities	Diagnostic tracking of molecular interactions

CONCLUSION

Silver nanoparticles (AgNPs) have emerged as a cornerstone of modern nanobiotechnology, offering versatile solutions across antibacterial, antiviral, and medical disciplines. Their ability to bypass traditional antibiotic resistance mechanisms through multi-pronged cellular disruption makes them primary candidates for treating multi-drug-resistant infections and complex biofilms. Beyond their role as potent antimicrobial agents, AgNPs demonstrate significant promise in oncology by inducing targeted apoptosis and in regenerative medicine by accelerating wound healing through enhanced fibroblast activity and controlled inflammatory responses. Furthermore, their unique optical properties and surface modifiability facilitate high-precision bioimaging and the development of sensitive biosensors. As research shifts from basic validation to exploring complex molecular interactions and synergistic applications, AgNPs are poised to play an increasingly vital role in advanced therapeutic and diagnostic technologies.

REFERENCES

1. Chegini, P.; Salimi, F.; Zare, E.N.; Farrokh, P. Biogenic Synthesis of Antibacterial and Antioxidant Silver Nanoparticles Using Enterococcus Faecium DU.FS-Derived Exopolysaccharides: A Sustainable Approach for Green Nanotechnology. J. Polym. Environ, 2024; 1–16.
2. Mussin, J.; Giusiano, G. Synergistic Antimicrobial Activity of Biogenic Silver Nanoparticles and Acanthospermum Australe Essential Oil against Skin Infection Pathogens. Antibiotics, 2024; 13: 674.
3. Ipe, D.S.; Kumar, P.T.S.; Love, R.M.; Hamlet, S.M. Silver Nanoparticles at Biocompatible Dosage Synergistically Increases Bacterial Susceptibility to Antibiotics. Front. Microbiol, 2020; 11: 1074.
4. Khalil, M.A.; El Maghraby, G.M.; Sonbol, F.I.; Allam, N.G.; Ateya, P.S.; Ali, S.S. Enhanced Efficacy of Some Antibiotics in Presence of Silver Nanoparticles Against Multidrug Resistant Pseudomonas Aeruginosa Recovered from Burn Wound Infections. Front. Microbiol, 2021; 12: 648560.
5. Jackson, J.; Shademani, A.; Dosanjh, M.; Dietrich, C.; Pryjma, M.; Lambert, D.M.; Thompson, C.J. Combinations of Cannabinoids with Silver Salts or Silver Nanoparticles for Synergistic Antibiotic Effects against Methicillin-Resistant Staphylococcus aureus. Antibiotics, 2024; 13: 473.
6. Baselga, M.; Uranga-Murillo, I.; De Miguel, D.; Arias, M.; Sebastián, V.; Pardo, J.; Arruebo, M. Silver Nanoparticles–Polyethyleneimine-Based Coatings with Antiviral Activity against SARS-CoV-2: A New Method to Functionalize Filtration Media. Materials, 2022; 15: 4742.
7. Ismail, G.A.; El-Sheekh, M.M.; Samy, R.M.; Gheda, S.F. Antimicrobial, Antioxidant, and Antiviral Activities of Biosynthesized Sil- ver Nanoparticles by Phycobiliprotein Crude Extract of the Cyanobacteria Spirulina Platensis and Nostoc Linckia. BioNanoScience, 2021; 11: 355–370.
8. Al-Askar, A.A.; Aseel, D.G.; El-Gendi, H.; Sobhy, S.; Samy, M.A.; Hamdy, E.; El-Messeiry, S.; Behiry, S.I.; Elbeaino, T.; Abdelkhalek,Antiviral Activity of Biosynthesized Silver Nanoparticles from Pomegranate (Punica granatum L.) Peel Extract against Tobacco Mosaic Virus. Plants, 2023; 12: 2103.
9. Abdelkhalek, A.; Yassin, Y.; Abdel-Megeed, A.; Abd-Elsalam, K.; Moawad, H.; Behiry, S. Rhizobium Leguminosarum Bv. Viciae- Mediated Silver Nanoparticles for Controlling Bean Yellow Mosaic Virus (BYMV) Infection in Faba Bean Plants. Plants, 2022; 12: 45.
10. Wang, D.; Yin, C.; Bai, Y.; Zhou, M.; Wang, N.; Tong, C.; Yang, Y.; Liu, B. Chitosan-Modified AgNPs

Efficiently Inhibit Swine Coronavirus-Induced Host Cell Infections via Targeting the Spike Protein. Biomolecules, 2024; 14: 1152.

11. Hashem, A.H.; Saied, E.; Amin, B.H.; Alotibi, F.O.; Al-Askar, A.A.; Arishi, A.A.; Elkady, F.M.; Elbahnasawy, M.A. Antifungal Activity of Biosynthesized Silver Nanoparticles (AgNPs) against Aspergilli Causing Aspergillosis: Ultrastructure Study. J. Funct. Biomater, 2022; 13: 242.
12. Mare, A.D.; Ciurea, C.N.; Man, A.; Mares, , M.; Toma, F.; Bert, a, L.; Tanase, C. In Vitro Antifungal Activity of Silver Nanoparticles Biosynthesized with Beech Bark Extract. Plants, 2021; 10: 2153.
13. Li, L.; Pan, H.; Deng, L.; Qian, G.; Wang, Z.; Li, W.; Zhong, C. The Antifungal Activity and Mechanism of Silver Nanoparticles against Four Pathogens Causing Kiwifruit Post-Harvest Rot. Front. Microbiol, 2022; 13: 988633.
14. Liu, X.; Li, T.; Cui, X.; Tao, R.; Gao, Z. Antifungal Mechanism of Nanosilver Biosynthesized with Trichoderma Longibrachiatum and Its Potential to Control Muskmelon Fusarium Wilt. Sci. Rep, 2024; 14: 20242.
15. Vicencio-Salas Solís, C.; Zavaleta-Mancera, H.A.; García-Díaz, S.E.; García-Nava, R.; Trejo-Téllez, L.I.; Robledo-Paz, A. Green Synthesis of Silver Nanoparticles Using Cedrela Odorata and Their Fungicidal Activity against Fusarium Circinatum. J. Nanopart. Res, 2024; 26: 164.
16. Scandorieiro, S.; De Oliveira, N.R.; De Souza, M.; De Castro-Hoshino, L.V.; Baesso, M.L.; Nakazato, G.; Kobayashi, R.K.T.; Panagio, L.A.; Lonni, A.A.S.G. Nail Lacquer Containing Origanum Vulgare and Rosmarinus Officinalis Essential Oils and Biogenic Silver Nanoparticles for Onychomycosis: Development, Characterization, and Evaluation of Antifungal Efficacy. Antibiotics, 2024; 13: 892.
17. Mouzahim, M.E.; Eddarai, E.M.; Eladaoui, S.; Guenbour, A.; Bellaouchou, A.; Zarrouk, A.; Boussen, R. Effect of Kaolin Clay and Ficus Carica Mediated Silver Nanoparticles on Chitosan Food Packaging Film for Fresh Apple Slice Preservation. Food Chem, 2023; 410: 135470.
18. Zhao, X.; Tian, R.; Zhou, J.; Liu, Y. Multifunctional Chitosan/Grape Seed Extract/Silver Nanoparticle Composite for Food Packaging Application. Int. J. Biol. Macromol, 2022; 207: 152–160.
19. He, Y.; Li, H.; Fei, X.; Peng, L. Carboxymethyl Cellulose/Cellulose Nanocrystals Immobilized Silver Nanoparticles as an Effective Coating to Improve Barrier and Antibacterial Properties of Paper for Food Packaging Applications. Carbohydr. Polym, 2021; 252: 117156.
20. Hamouda, R.A.; Almaghrabi, F.Q.; Alharbi, O.M.; Al-Harbi, A.D.M.; Alsulami, R.M.; Alhumairi, A.M. Antifungal Activities of Biogenic Silver Nanoparticles Mediated by Marine Algae: In Vitro and In Vivo Insights of Coating Tomato Fruit to Protect against Penicillium Italicum Blue Mold. Mar. Drugs, 2024; 22: 225.
21. Lateef, A.; Adelere, I.A.; Gueguim-Kana, E.B.; Beukes, L.S.; Matyumza, N. Evaluation of Feather Hydrolysate-Mediated Silver Nanoparticles as Biofertilizers for the Enhancement of Vegetative Growth and Nutraceutical Properties of Vegetables. Nanotechnol. Environ. Eng, 2024; 9: 47–65.
22. Takallu, S.; Kakian, F.; Bazargani, A.; Khorshidi, H.; Mirzaei, E. Development of Antibacterial Collagen Membranes with Optimal Silver Nanoparticle Content for Periodontal Regeneration. Sci. Rep, 2024; 14: 7262.
23. Holguín-Meráz, C.; Martínez-Martínez, R.E.; Zaragoza-Contreras, E.A.; Domínguez-Pérez, R.A.; Reyes-López, S.Y.; Donohue- Cornejo, A.; Cuevas-González, J.C.; Silva-Benítez, E.D.L.; Molina-Frechero, N.; Espinosa-Cristóbal, L.F. Antibacterial Effect of Silver Nanoparticles against Oral Biofilms in Subjects with Motor and Intellectual Disabilities. J. Funct. Biomater, 2024; 15: 191.
24. Navarrete-Olvera, K.; Niño-Martínez, N.; De Alba-Montero, I.; Patiño-Marín, N.; Ruiz, F.; Bach, H.; Martínez-

Castañón, G.-A. The Push-Out Bond Strength, Surface Roughness, and Antimicrobial Properties of Endodontic Bioceramic Sealers Supplemented with Silver Nanoparticles. Molecules, 2024; 29: 4422.

25. Jasso-Ruiz, I.; Velazquez-Enriquez, U.; Scougall-Vilchis, R.J.; Morales-Luckie, R.A.; Sawada, T.; Yamaguchi, R. Silver Nanoparticles in Orthodontics, a New Alternative in Bacterial Inhibition: In Vitro Study. Prog. Orthod, 2020; 21: 24.
26. Ahmed, A.; Muhammad, N.; Ali, A.; Mutahir, Z.; Khan, A.S.; Sharif, F.; Shah, A.T.; Haq, Z.U.; Liaqat, S.; Khan, M.A. Effect of Augmentin-Coated Silver Nanoparticles on Biological and Mechanical Properties of Orthodontic Bracket Cement. Mater. Technol, 2022; 37: 2983–2994.
27. Guo, C.; Cui, W.; Wang, X.; Lu, X.; Zhang, L.; Li, X.; Li, W.; Zhang, W.; Chen, J. Poly-L-Lysine/Sodium Alginate Coating Loading Nanosilver for Improving the Antibacterial Effect and Inducing Mineralization of Dental Implants. ACS Omega, 2020; 5: 10562–10571.
28. Wypij, M.; Je˛drzejewski, T.; Trzcin´ska-Wencel, J.; Ostrowski, M.; Rai, M.; Golin´ska, P. Green Synthesized Silver Nanoparticles: Antibacterial and Anticancer Activities, Biocompatibility, and Analyses of Surface-Attached Proteins. Front. Microbiol, 2021; 12: 632505.
29. Bhunia, A.K. Introduction to Foodborne Pathogens. In Foodborne Microbial Pathogens; Food Science Text Series; Springer: NewYork, NY, USA, 2018; pp. 1–23, ISBN 978-1-4939-7347-7.
30. Anvar, A.A.; Ahari, H.; Ataee, M. Antimicrobial Properties of Food Nanopackaging: A New Focus on Foodborne Pathogens. Front. Microbiol, 2021; 12: 690706.
31. Pradhan, N.; Singh, S.; Ojha, N.; Shrivastava, A.; Barla, A.; Rai, V.; Bose, S. Facets of Nanotechnology as Seen in Food Processing, Packaging, and Preservation Industry. BioMed Res. Int, 2015; 2015: 1–17.
32. Realini, C.E.; Marcos, B. Active and Intelligent Packaging Systems for a Modern Society. Meat Sci, 2014; 98: 404–419.
33. Dash, K.; Deka, P.; Bangar, S.; Chaudhary, V.; Trif, M.; Rusu, A. Applications of Inorganic Nanoparticles in Food Packaging: A Comprehensive Review. Polymers, 2022; 14: 521.
34. Istiqola, A.; Syafiuddin, A. A Review of Silver Nanoparticles in Food Packaging Technologies: Regulation, Methods, Properties, Migration, and Future Challenges. J. Chin. Chem. Soc, 2020; 67: 1942–1956.