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Review Article

A Comprehensive Overview of Virus-Mediated Synthesis of Silver Nanoparticles

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ABSTRACT

Virus-mediated synthesis of silver nanoparticles (AgNPs) is an emerging and eco-friendly approach that leverages the biotemplating ability of viruses for controlled nanoparticle formation. Unlike conventional chemical and physical synthesis methods, this biogenic approach utilizes viruses as scaffolds and reducing agents to facilitate AgNP nucleation and growth. Various viruses, including plant viruses (e.g., Tobacco mosaic virus), bacteriophages (e.g., M13 phage), and animal viruses (e.g., Influenza virus), have been explored for their ability to template AgNPs with precise size and morphology. This method offers several advantages, including enhanced monodispersity, biocompatibility, and sustainability. Virus-templated AgNPs find applications in diverse fields, such as antimicrobial treatments, biosensing, catalysis, and nanoelectronics. However, challenges related to scalability, stability, and biosafety must be addressed to enable widespread industrial and biomedical applications. This article provides a comprehensive overview of virus-mediated AgNP synthesis, discussing its mechanisms, advantages, challenges, and future prospects.

Keywords: Virus-mediated, Silver, Nanoparticles.

INTRODUCTION

Nanotechnology has revolutionized various scientific fields, including medicine, electronics, and environmental sciences. Among different nanomaterials, silver nanoparticles (AgNPs) have attracted immense attention due to their unique antimicrobial, optical, and catalytic properties. Various physical and chemical methods exist for synthesizing AgNPs; however, these approaches often involve toxic chemicals and high energy consumption.[1]

Biogenic synthesis has emerged as a sustainable alternative, utilizing biological entities such as plants, fungi, bacteria, and viruses for nanoparticle production.[2] In particular, viruses have gained interest due to their well-defined nanostructures, ability to self-assemble, and biocompatibility.[1,2] This article explores the virus-mediated synthesis of AgNPs, focusing on mechanisms, types of viruses used, and potential applications.

Mechanism of Virus-Mediated Silver Nanoparticle Synthesis

The virus-mediated synthesis of AgNPs occurs through a biomineralization process, where viruses act as templates for the nucleation and growth of nanoparticles.[1] The general mechanism can be described in the following steps.[3]

Binding of silver ions (Ag^+)

The binding of silver ions (Ag^+) to viral protein capsids is a key mechanism underlying silver's antiviral properties. Since viral capsids contain functional groups such as amines ($-NH_2$), thiols (-SH), hydroxyl (-OH), and carboxyl ($-COO^-$), they provide multiple sites for Ag^+ interactions.[4]

Reduction of silver ions

The viral capsid proteins or genetic material mediate the reduction of Ag^+ to Ag^0, initiating nanoparticle formation. The reduction of silver ions (Ag^+) to elemental silver (Ag^0) by viral capsid proteins or genetic material is a fascinating process that leads to the *in-situ* formation of AgNPs. This process is a form of biogenic nanoparticle synthesis, where biological molecules act as reducing and stabilizing agents. External factors such as pH, temperature, and light exposure can enhance this reduction process.[5]

Nucleation and growth of AgNPs

The reduced silver atoms aggregate and nucleate on the viral surface, leading to the formation of well-defined nanoparticles. The process of AgNP formation on the viral surface is a fascinating example of biotemplated nanomaterial synthesis.[6] The nucleation and aggregation of reduced Ag^0 atoms on the virus result in well-defined nanoparticles, whose size and morphology can be fine-tuned by modifying the reaction conditions and virus type.

Types of Viruses used in Silver Nanoparticle Synthesis

Plant viruses

Plant viruses provide an excellent biotemplating platform for the synthesis of silver nanoparticles (AgNPs) due to their highly organized, symmetrical protein capsids.[7] Their precise nanostructures, stability, and well-defined surface chemistry make them ideal scaffolds for controlled AgNP nucleation and growth. Plant viruses have self-assembling icosahedral or rod-like capsids that serve as templates for AgNP formation and their uniform surface chemistry ensures consistent nanoparticle size and shape. Plant viruses are non-toxic to humans and provide a green chemistry approach to AgNP synthesis and they also eliminate the need for harsh chemical-reducing agents.[7] Some examples of plant viruses used in AgNP synthesis are (Figure 1).

- *Tobacco mosaic virus (TMV)*

A rod-shaped virus that provides a template for elongated AgNPs [8]. TMV is a rigid rod-like virus (300 nm long, 18 nm diameter), providing a linear platform for nanowire or nanorod formation.[8] AgNPs can nucleate along the virus length, forming uniformly distributed nanoparticles.

- *Cowpea mosaic virus (CPMV)*

An icosahedral virus with surface functional groups facilitating Ag^+ reduction. CPMV has a highly symmetrical, icosahedral capsid (30 nm diameter) with exposed amine and carboxyl groups.[9] AgNPs can attach and grow on specific capsid sites, leading to monodisperse and spherical nanoparticles.

- *Brome mosaic virus (BMV)*

BMV forms hollow, capsid-like nanocages that can encapsulate Ag^+ ions, leading to internalized AgNP formation.[10]

- *Potato virus X (PVX)*

PVX is a flexible filamentous virus that supports anisotropic AgNP growth, forming nanowires or nanorods.[11]

Virus-templated AgNPs are useful for enhanced antiviral and antibacterial surfaces in the antimicrobial coating, used as biosensors for the detection of pathogens and toxins, improved chemical reaction efficiency and useful for targeted drug delivery in nanomedicines.[7] Plant viruses serve as structurally organized, templating platforms for AgNP synthesis. Their precise capsid symmetry, functional groups, and biocompatibility allow for controlled nanoparticle growth, unlocking novel applications in medicine, electronics, and materials science.

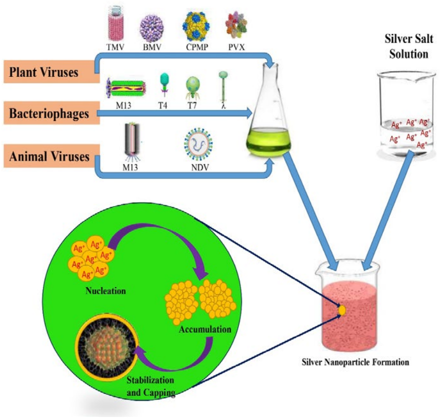

Figure 1: Graphical representation of mechanism of virus-mediated synthesis of silver nanoparticles

Bacteriophages

Bacteriophages (viruses that infect bacteria) serve as biotemplates for the controlled synthesis of AgNPs. Their well-defined capsid structures, genetic tunability, and unique surface chemistry make them excellent platforms for designing AgNPs with precise size, shape, and functionality.[12] Some examples o of bacteriophages used in AgNP synthesis are Figure 2.

- *M13 bacteriophage (Filamentous phage)*

It is a long, filamentous virus (~880 nm long, 6.6 nm diameter). Silver ions adsorb along the phage's length, leading to nanowire or nanorod formation. M13 bacteriophage biotempletes AgNPs enhanced conductivity in silver-based electronic devices, improved reaction efficiency and were useful in water purification and wound dressings.[12]

- *T4 bacteriophage (Icosahedral head with tail fibers)*

It is an icosahedral capsid (~90 nm) with a contractile tail. Silver nucleates on the capsid and form the spherical AgNPs. T4 bacteriophage biotempletes AgNPs act as antiviral & antibacterial agents and improve bacterial targeting during phase therapy enhancement.[12]

- *T7 bacteriophage (Small icosahedral phage)*

It has a compact, icosahedral head (~50 nm) like structure. T7 bacteriophage produces uniform, monodisperse AgNPs (~10–20 nm). T7 bacteriophage templates AgNPs are used in targeted cancer therapy through drug delivery and enhanced light-based cancer treatments in photochemical therapy.[12]

- *λ (Lambda) Phage*

It has an icosahedral capsid (~63 nm) with a flexible tail-like structure. λ (Lambda) phage functionalized capsid binds and stabilizes AgNPs. AgNP-coated λ phages detect heavy metals and toxins in environmental sensing and in nanophotonics.[12]

Bacteriophages offer a unique, bioengineered approach to synthesizing highly controlled AgNPs. Their structural precision, genetic modifiability, and functional diversity make them ideal templates for applications in medicine, electronics, and nanotechnology.[12]

Animal Viruses

Several animal viruses (Figure 2) have been explored for the synthesis of AgNPs due to their self-assembling properties, ability to act as biological templates and defined capsid structures.[12,13]

- *Bacteriophage M13*

The bacteriophage, a filamentous virus that infects bacteria, has been utilized as a biological scaffold for the synthesis of various nanoparticles.[12,13] Its major coat proteins provide reactive sites for nanoparticle formation.

- *Newcastle disease virus (NDV)*

Newcastle disease virus (NDV), which primarily infects birds, has been investigated for its interaction with AgNPs. Studies have demonstrated that AgNPs synthesized using green methods exhibit potent antiviral effects against NDV, suggesting potential therapeutic applications.[13]

Advantages of Virus-Mediated Silver Nanoparticles Synthesis

Virus-mediated synthesis of AgNPsoffers several advantages over conventional chemical and physical methods, making it an attractive approach for nanomaterial production. One of the key benefits is biotemplating precision, where viruses provide highly organized and uniform nanoscale structures that enable controlled nucleation and growth of AgNPs, resulting in monodisperse nanoparticles with well-defined shapes and sizes.[14] Additionally, this method is eco-friendly and sustainable, eliminating the need for toxic chemical-reducing agents and harsh reaction conditions, thereby promoting green nanotechnology. The genetic tunability of viruses allows for the engineering of capsid surface functionalities, enabling customized nanoparticle synthesis for specific applications. Moreover, virus-templated AgNPs exhibit enhanced stability and dispersibility, as the viral scaffolds prevent uncontrolled aggregation, leading to long-term functional nanoparticles. Another significant advantage is the biocompatibility and biomedical applicability of virus-mediated AgNPs, making them suitable for use in antimicrobial coatings, drug delivery, biosensing, and cancer therapy.[1,2,14] Furthermore, the self-assembling nature of viruses facilitates the formation of complex nanostructures, such as nanowires and nanocages, expanding their potential in nanoelectronics, catalysis, and environmental remediation. Overall, virus-mediated AgNP synthesis combines precision, sustainability, and functional versatility, positioning it as a powerful tool in nanotechnology and biomedicine.[1,2,14]

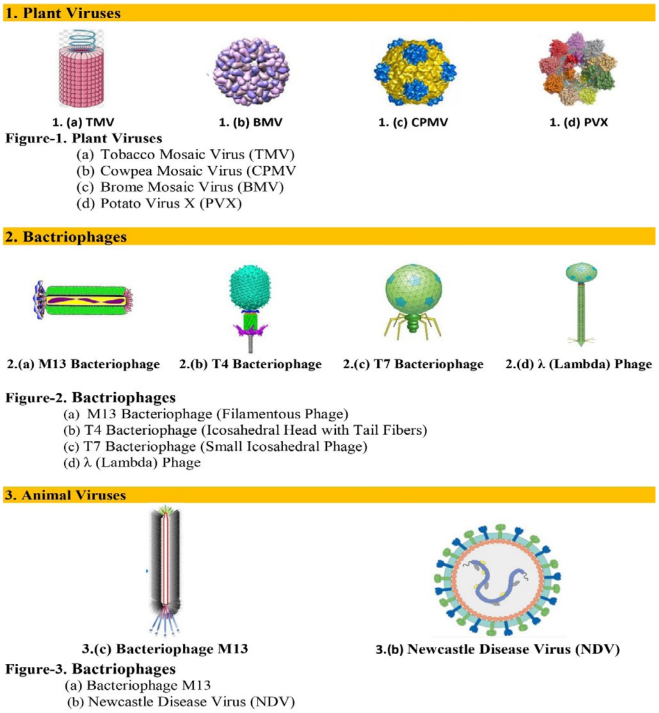

Figure 2: Diagrammatic representation of types of viruses used in the synthesis of silver nanoparticles

Applications of Virus-Mediated Silver Nanoparticles Synthesis

Virus-mediated AgNPshave emerged as a promising nanomaterial with diverse applications across multiple fields. Their precisely controlled size, shape, and surface properties, achieved through viral templating, make them highly effective in biomedical, environmental, and technological applications.[14,15] In biomedicine, virus-templated AgNPs exhibit strong antiviral, antibacterial, and antifungal properties, making them valuable for use in antimicrobial coatings, wound dressings, and infection-resistant medical implants. Additionally, their ability to disrupt viral capsids and inhibit viral replication has led to potential applications in antiviral therapies. In drug delivery and nanomedicine, virus-AgNP hybrids enable targeted cancer therapy, photothermal treatment, and gene delivery, where the viral template provides specificity while AgNPs enhance therapeutic efficacy.[1,2,14,15] Beyond medicine, virus-templated AgNPs play a key role in biosensing and diagnostics, improving the sensitivity of pathogen detection and environmental monitoring through plasmonic and electrochemical biosensors. In the field of nanoelectronics, filamentous viruses like M13 facilitate the formation of conductive silver nanowires, which are utilized in flexible electronics, energy storage devices, and smart coatings. Furthermore, in catalysis and environmental applications, virus-templated AgNPs serve as efficient catalysts for chemical reactions, pollutant degradation, and water purification, leveraging their high surface-to-volume ratio and enhanced reactivity. The ability to harness viruses as biofactories for eco-friendly AgNP synthesis further supports their potential for sustainable nanotechnology applications.[9,14,15]

Challenges and Future Prospects

Despite its potential, virus-mediated AgNP synthesis faces several challenges that must be addressed for broader application. One key limitation is scalability, as the controlled synthesis of virus-templated AgNPs is often limited to laboratory settings, making large-scale production complex and costly. Additionally, the stability and reproducibility of virus-mediated synthesis can vary due to environmental factors such as pH, temperature, and ionic strength, which influence nanoparticle formation. Another challenge is the biosafety and regulatory concerns associated with using viruses in nanotechnology, particularly in biomedical applications, where concerns about potential immunogenicity and biohazards must be addressed before clinical use. Furthermore, customization and functionalization of virus-templated AgNPs for specific applications require precise genetic or chemical modifications, which can be time-consuming and technically demanding.

The future of virus-mediated AgNP synthesis lies in overcoming these challenges through advancements in synthetic biology, genetic engineering, and nanotechnology integration. The development of genetically modified viruses with enhanced binding sites and stability will enable greater control over nanoparticle size and functionality. Improvements in bioreactor technology and scalable production methods will facilitate large-scale synthesis while maintaining precision and reproducibility. Additionally, research into hybrid virus-inorganic nanostructures will expand the applications of virus-templated AgNPs in biomedicine, catalysis, and nanoelectronics. Moreover, as regulatory frameworks evolve, standardized safety assessments and approval processes will help accelerate the adoption of virus-mediated AgNPs in clinical and industrial applications. With continuous innovation, virus-mediated AgNP synthesis holds the potential to revolutionize nanomedicine, environmental sustainability, and advanced material science, offering a biologically inspired, eco-friendly, and highly tunable approach to nanoparticle fabrication.

CONCLUSION

Virus-mediated synthesis of AgNPs represents an innovative and sustainable approach to nanomaterial fabrication, leveraging the structural precision, self-assembly, and biocompatibility of viruses as natural templates. This method enables highly controlled nanoparticle formation, producing AgNPs with uniform size, shape, and enhanced functional properties, making them superior to conventionally synthesized nanoparticles. Additionally, the eco-friendly nature of virus-templated synthesis, which eliminates the need for harsh chemicals, aligns with the principles of green nanotechnology. The versatility of virus-mediated AgNPs has unlocked significant advancements in biomedicine, electronics, catalysis, and environmental applications, with potential uses in antimicrobial therapies, biosensors, drug delivery systems, and nanowire-based electronics. As research continues to refine the genetic engineering of viruses and optimize nanoparticle synthesis conditions, virus-mediated AgNPs are poised to revolutionize various industries, offering a precise, sustainable, and multifunctional platform for next-generation nanotechnology applications.

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