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**Review Article**

# Silver Nanoclusters Versatile Applications An Updated Review

**Vaibhavi V. Kshatriya*, Manoj R. Kumbhare, Shraddha V. Jadhav, Prajakata J. Thorat, Rushikesh G. Bhambarge**

*Department of Pharmaceutical Chemistry, S.M.B.T. College of Pharmacy, Affiliated to Savitribai Phule Pune University, Dhamangaon, Nashik, M.S. India-422403.*

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## ABSTRACT

Silver nanoclusters (AgNCs) have emerged as versatile and promising agents in the field of biomedicine due to their unique characteristics and wide uses. This article presents a summary of the transformational role performed by AgNCs in scientific research and healthcare. It begins by describing the distinguishing properties of AgNCs and their historical context, stressing their expanding relevance across diverse biological areas. The paper highlights AgNCs' uses, including bioimaging, medicines, and illness detection, highlighting their potential to transform precision medicine and better patient outcomes. Additionally, it covers problems relating to AgNC safety and regulatory concerns while emphasizing upcoming frontiers in AgNC-enabled biomedical research. Silver nanoclusters are primed to continue altering the future of healthcare, opening the door for novel solutions and enhanced healthcare delivery.

## INTRODUCTION

Nanotechnology includes the manipulation and control of materials at the nanoscale, which is about 1 to 100 nanometers. In the world of biomedicine, nanotechnology has gained substantial attention because to its capacity to precisely target particular disease locations and administer therapeutic medicines with unmatched accuracy.[1], [2] Nanoparticles, such as silver nanoclusters, possess distinct physical and chemical characteristics compared to their bulk counterparts. These qualities originate from their tiny size, enormous surface area-to-volume ratio, and quantum effects, making them exceedingly flexible instruments in biological applications.

### 1.1. Rationale for Studying Silver Nanoclusters

Silver nanoclusters, in particular, have drawn substantial interest among academics due to their outstanding optical and electrical features. Their capacity to generate high fluorescence and absorb light at certain wavelengths makes them good candidates for bioimaging and biosensing

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***Corresponding Author:** Vaibhavi V. Kshatriya
**Address**: *Department of Pharmaceutical Chemistry, S.M.B.T. College of Pharmacy, Affiliated to Savitribai Phule Pune University, Dhamangaon, Nashik, M.S. India-422403.*
**Email** ✉: vaibhavikshatriya5086@gmail.com

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applications. Additionally, silver nanoclusters demonstrate extraordinary stability, biocompatibility, and variable size-dependent characteristics, making them appropriate for different biological uses. Their tiny size allows them to penetrate cellular barriers, enabling prospects for targeted medication administration and disease diagnostics at the molecular level.

## 2. Synthesis methods for AgNCs

AgNCs can be synthesized using various methods, each contributing to the control of their size, shape, and properties. These synthesis methods can be broadly categorized into chemical and physical approaches.[3]

### 2.1. Chemical Synthesis

Chemical synthesis is a typical approach used to create AgNCs. In this procedure, the selection of the silver precursor plays a key role in defining the characteristics of the nanoclusters. Different silver precursors can lead to changes in size, stability, and optical characteristics of the resultant AgNCs. Stabilizing agents serve a vital role in regulating the size and form of AgNCs during chemical synthesis. By altering the concentrations and qualities of these substances, researchers may fine-tune the final result. The choice of stabilizing agent can impact the stability of AgNCs, their dispersibility in solvents, and their compatibility with diverse systems. Traditional chemical reduction procedures are routinely applied to produce AgNCs. These procedures include reducing silver ions in a solution to generate AgNCs. The use of reducing chemicals, such as sodium borohydride or hydrazine, provides for fine control over the reduction process and the resultant nanocluster characteristics.[4]

Green synthesis techniques have gained popularity in recent years due to their eco-friendly character. These technologies employ natural and sustainable resources, such as plant extracts or biomolecules, as reducing and stabilizing agents. Green synthesis not only offers environmental benefits but also gives unique chances to modify the characteristics of AgNCs for specific medicinal applications.[5], [6]

### 2.2. Physical Synthesis

Physical synthesis approaches offer different paths for the creation of AgNCs with specific properties. These approaches leverage physical processes rather than chemical interactions to manufacture nanoclusters. Laser ablation-based methods are one such physical synthesis approach employed for AgNC production. In this method, a high-intensity laser is focused on a silver target, resulting in the creation of AgNCs by vaporization and condensation. The characteristics of the created AgNCs may be carefully adjusted by modifying laser parameters, such as energy density, pulse length, and repetition rate. Cluster beam deposition is another physical synthesis process applied to generate AgNC films and coatings. In this approach, AgNCs are generated in a cluster source and deposited onto a solid substrate. The size and arrangement of AgNCs in the resultant thin films may be precisely tailored by manipulating the deposition process. Gas-phase synthesis techniques enable large-scale manufacturing of AgNCs. These procedures include vaporizing silver precursors and enabling them to react and condense in a controlled environment, resulting in the creation of AgNCs. Many approaches, including as gas condensation, thermal evaporation, and aerosol processes, are applied in gas-phase synthesis to manufacture size-controlled and monodisperse AgNCs. By applying a mix of chemical and physical production methods, researchers may exploit the unique features of AgNCs for a wide range of biological applications. These approaches enable for the exact control of nanocluster size, shape, stability, and other features, providing personalized solutions for varied healthcare and diagnostic applications.[7] As the science continues to grow fast, the utilization of silver nanoclusters is set to revolutionize biomedical applications, bringing up new possibilities in fields like as drug delivery, imaging, sensing, and therapies. With continued research and development, we may anticipate to observe even more remarkable developments in employing silver nanoclusters in biomedical sciences.[8]

## 3. Characterization of AgNCs

AgNCs, being at the forefront of nanomaterial research, require various characterization techniques to understand their properties and behavior accurately. The key characterization techniques employed for AgNCs can be broadly categorized into spectroscopic and structural characterization.[9], [10]

### 3.1. Spectroscopic Characterization

Spectroscopic methods play a crucial role in examining the optical properties and fluorescence enhancements of AgNCs. By analyzing the absorption and emission spectra of AgNCs, researchers gain valuable insights into their electronic structure, surface plasmon resonance, and energy states.[11], [12]polymorphic forms (2). Poorly water-soluble active Pharmaceutical ingredients (APIs) may undergo incomplete dissolution in gastrointestinal fluids and thus be only partially absorbed into the systemic Circulation As it is reported, 40% of commercialized APIs and almost 70% of potential new drugs are poorly water-soluble (3) The main objective of this work they show the impact of antisolvent on the dissolution rate of the poorly

#### 1. UV-visible Spectroscopy for Studying Absorption and Emission Spectra

UV-visible spectroscopy is a widely used technique to study the absorption and emission spectra of AgNCs. By subjecting AgNC samples to ultraviolet or visible light, researchers can measure the extent of light absorption and observe their unique optical properties. This technique aids in determining the energy levels and electronic transitions within the AgNCs, providing critical details about their photophysical properties.

#### 2. Fluorescence Enhancements and Mechanisms in AgNCs

One of the remarkable features of AgNCs is their ability to exhibit enhanced fluorescence compared to bulk silver. Spectroscopic techniques, combined with fluorescence spectroscopy, allow researchers to investigate the mechanisms behind this phenomenon. By studying the excited state dynamics and surface passivation of AgNCs, scientists can uncover the intricate processes that lead to fluorescence enhancements.

#### 3. Raman Spectroscopy: Probing the Vibrational Modes of AgNCs

Raman spectroscopy serves as a powerful tool to understand the vibrational modes and structural characteristics of AgNCs. This technique provides valuable information about the bond vibrations, crystal symmetry, and molecular interactions within the nanoclusters. By analyzing the Raman scattering patterns, researchers can gain insights into the unique chemical and physical properties of AgNCs.[13]–[15]

### 3.2 Structural Characterization

Understanding the precise structure and morphology of AgNCs is essential for tailoring their properties and designing specific biomedical applications. Several advanced techniques are employed to probe the structural characteristics of AgNCs.

#### A. X-ray Crystallography: Determining AgNC Crystal Structures

X-ray crystallography is a well-established technique for determining the crystal structures of various materials, including AgNCs. By subjecting AgNC crystals to X-ray diffraction, researchers can obtain precise information about the arrangement of atoms within the nanoclusters. This technique enables the determination of atomic positions, crystal symmetry, and interatomic distances, ultimately providing a detailed understanding of the structural properties of AgNCs.[16], [17]

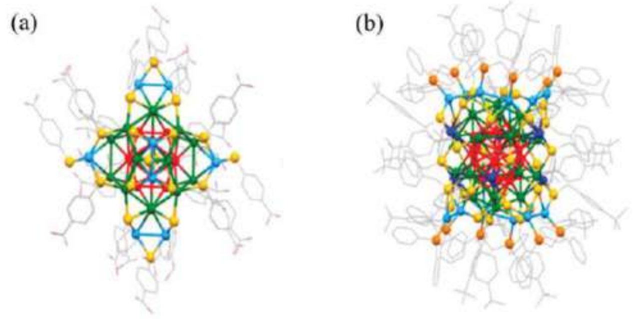

**Fig. 1: Crystal structures of the Ag44(SPhCO2H2)30 and the Ag50(TBBM)30-(dppm)6 nanoclusters (Copyright 2017, American Chemical Society)**

### B. Transmission Electron Microscopy for Visualizing AgNC Size and Morphology

Transmission electron microscopy (TEM) plays a crucial role in visualizing the size, shape, and morphology of AgNCs. By bombarding AgNC samples with a beam of electrons, researchers can obtain high-resolution images that reveal intricate details of the nanoclusters' structure. TEM allows for the precise measurement of particle size, evaluation of uniformity, and identification of any surface defects or impurities present in AgNCs.[18]

### C. Scanning Probe Microscopy: High-resolution Imaging of AgNCs

Scanning probe microscopy techniques, such as atomic force microscopy (AFM) and scanning tunneling microscopy (STM), provide exceptional resolution and surface sensitivity for imaging AgNCs. These techniques allow researchers to visualize individual nanoclusters and characterize their surface topography with nanometer-scale precision. By employing scanning probe microscopy, scientists can examine the surface roughness, charge distribution, and even manipulate the individual AgNCs, opening doors for advanced nanoscale engineering.[19], [20]

## 4. Imaging applications of AgNCs

### 4.1. Bioimaging with AgNCs

Bioimaging plays a critical role in the field of biomedical research and diagnostics. With the advent of silver nanoclusters (AgNCs), a new era of highly efficient and versatile bioimaging has emerged. AgNCs, due to their unique properties, have become a promising tool for cellular and tissue imaging. These tiny particles, with sizes typically ranging from 1 to 10 nanometers, possess extraordinary fluorescence properties, making them ideal candidates for various bioimaging techniques.

### A. Fluorescent AgNCs for cellular and tissue imaging

Fluorescent AgNCs have gained significant attention in the field of bioimaging. Their small size allows for efficient cellular uptake and distribution, enabling researchers to accurately observe and study cellular processes. With their exceptional photostability and high quantum yield, AgNCs provide enhanced signal-to-noise ratios, thus improving the resolution and sensitivity of cellular and tissue imaging. This breakthrough has opened up new opportunities for unraveling complex biological mechanisms at the molecular level.[21], [22]

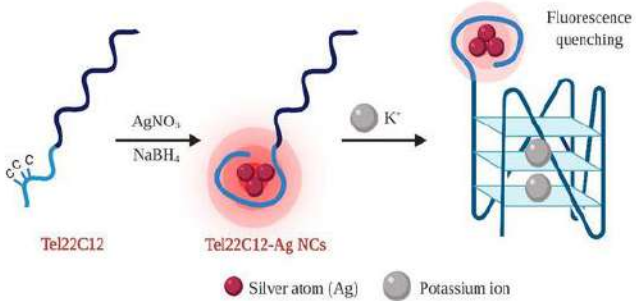

**Fig 2: Illustration shows the working idea of Fluorescent –AgNCs**

**Table 1: overview of key properties of the AgNC-based systems from the Studies Mentioned in the AuNCs in Fluorescent Bioimaging Section**

| Property | Study |
|---|---|
| Size | 2-10 nm |
| Shape | Spherical, rod-like, or triangular |
| Surface | Stabilized by capping agents such as citrate, thiols, or polymers |

| | |
|---|---|
| Luminescence | Emission maxima in the visible or near-infrared region |
| Photostability | Good photostability under physiological conditions |
| Biocompatibility | Biocompatible with cells and tissues |
| Applications | Cancer therapy, antibacterial activity, antioxidant activity, anti-inflammatory activity, anti-allergic activity, and bioimaging |

### B. AgNCs as contrast agents for improving medical imaging techniques

AgNCs have demonstrated enormous promise as contrast agents for medical imaging procedures including computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound. These nanoclusters possess exceptional X-ray attenuation, superb magnetic characteristics, and extraordinary acoustic qualities, respectively. By adding AgNCs into various imaging modalities, researchers can increase the visibility of certain tissues or organs, leading to more accurate diagnoses and focused therapies. This achievement signifies a significant improvement in the realm of medical imaging, supporting physicians in making more informed judgments.[23], [24]

### C. Multimodal imaging: Combining AgNCs with other imaging agents

The versatility of AgNCs allows for their integration with other imaging agents, enabling multimodal imaging. By combining AgNCs with organic dyes, quantum dots, or magnetic nanoparticles, researchers can simultaneously exploit the unique properties of each component. These multimodal imaging systems provide complementary information, improving the overall accuracy and reliability of biomedical imaging. The integration of AgNCs into multimodal imaging platforms holds great promise for the future, facilitating a deeper understanding of complex diseases and guiding personalized treatment strategies.

## 4.2 AgNCs in In Vivo Imaging

AgNCs have revolutionized in vivo imaging, where imaging is performed inside living organisms, including animals and humans. These remarkable nanoclusters offer unique advantages over conventional imaging techniques, enabling non-invasive visualization of deep tissues, tracking and monitoring systems, as well as simultaneous imaging and therapy.[25], [26]

### A. Tracking and monitoring systems using AgNCs in living organisms

AgNCs have evolved as significant instruments for tracking and monitoring systems within live organisms. Whether it's researching the migration of cells in regenerative medicine or monitoring the dispersion of drug delivery systems, AgNCs offer real-time imaging capabilities. Due to their constant fluorescence and perfect biocompatibility, these nanoclusters may be readily tracked and monitored, unraveling complicated biological processes with remarkable accuracy. The capacity to view the dynamic activity of cells and drug delivery devices in vivo holds tremendous potential for enhancing therapeutic treatments and understanding disease progression.[27]

### B. AgNC-based photoacoustic imaging for deep tissue visualization

Deep tissue visualization has been a major barrier in biomedical imaging, but AgNCs have given a new dimension to the field with their photoacoustic imaging capabilities. AgNCs show outstanding photothermal characteristics, absorbing light energy and creating sonic signals that may be monitored with great sensitivity. By applying AgNCs as contrast agents in photoacoustic imaging, researchers may penetrate deep tissues, seeing anatomical features and molecular processes with extraordinary detail. This revelation has opened up several opportunities for comprehending illnesses in their entirety and designing specific treatment methods.[28]

### C. Theranostic applications: AgNCs for simultaneous imaging and therapy

Theranostics, the merging of diagnostics and therapies, has attracted substantial interest in recent years. AgNCs have emerged as intriguing candidates for theranostic applications, concurrently performing imaging and therapeutic activities. By exploiting AgNCs as delivery vehicles for pharmaceuticals or therapeutic agents while keeping their labeling properties, researchers may accurately monitor drug distribution and therapeutic efficacy in real-time. This breakthrough method paves the possibility for customized medicine, giving individualized therapies based on real-time imaging input.

## 5. Therapeutic role of AgNCs

Silver Nanoclusters (AgNCs) have emerged as a potential tool in the field of biomedicine due to their unique features and various uses. These small clusters of silver atoms, ranging from 1 to 10 nanometers in size, show enormous promise in numerous therapeutic activities. This article discusses the tremendous developments and promise of AgNCs in revolutionizing biomedical applications, notably concentrating on their antibacterial characteristics and their involvement in cancer therapy.[29]–[31]

### 5.1. Antibacterial Applications

AgNCs have exhibited excellent antibacterial activity, giving them an intriguing alternative to standard antibiotics. Their methods of antimicrobial activity have been thoroughly researched and determined to be diverse, involving the breakdown of bacterial cell membranes, interference with critical metabolic activities, and creation of oxidative stress. These varied methods make it tough for bacteria to build resistance against AgNCs, therefore giving a viable option to tackle drug-resistant bacteria.

#### 1. Mechanisms of AgNC antimicrobial activity

AgNCs possess the ability to disrupt bacterial cell membranes, causing leakage of cellular components and eventual cell death. Additionally, AgNCs can penetrate the bacterial cell wall and interact with intracellular components, leading to the inhibition of vital enzymes and metabolic processes. Moreover, AgNCs generate reactive oxygen species (ROS) within bacteria, inducing oxidative stress and damaging essential biomolecules.[32], [33]

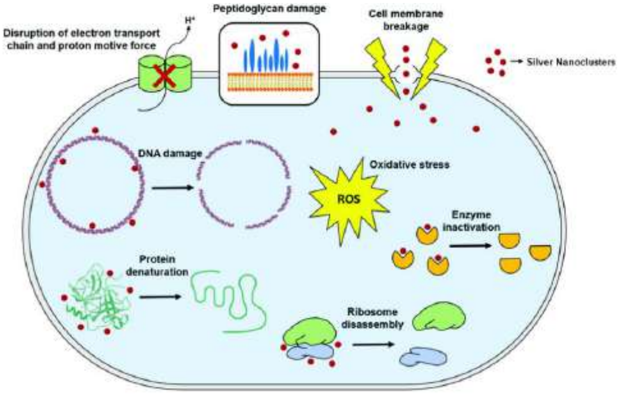

**Fig 3: Mechanisms of AgNC antimicrobial activity**

#### 2. AgNCs for combating drug-resistant bacteria

The rise of antibiotic-resistant bacteria has become a global health concern. However, AgNCs show promise in addressing this problem. Due to their unique mechanism of action, which differs from traditional antibiotics, AgNCs can effectively combat drug-resistant bacteria. This alternative approach provides hope for the development of new antibacterial strategies and the prevention of antibiotic resistance.[34], [35]

#### 3. Wound dressing and implant coatings using AgNCs

In addition to their antimicrobial properties, AgNCs can be incorporated into wound dressings and implant coatings to prevent infection. By incorporating these nanoclusters into the fabric of wound dressings or coating them onto the surface of implants, a continuous release of silver ions can occur, effectively inhibiting bacterial growth and reducing the risk of infection. This application holds great promise in the field of biomedical engineering, where the prevention of surgical site infections is of utmost importance.[36]–[38]

**Table 2: Antibacterial applications of various silver nanoclusters**

| Silver Nanoclusters | Applications |
|---|---|
| Silver nanoparticles | Wound dressings, bandages, surgical implants, catheters, contact lenses, toothpaste, mouthwash, deodorant, textiles, food packaging, water treatment |
| Silver nanorods | Antifouling coatings, wound dressings, drug delivery systems |
| Silver nanowires | Sensors, electronics, tissue engineering |
| Silver nanoclusters | Antibacterial paints, coatings, adhesives, cosmetics, sunscreen |

### 5.2. Cancer Therapy with AgNCs

Apart from their antibacterial applications, AgNCs have shown remarkable potential in the field of cancer therapy. The unique optical properties of AgNCs make them suitable for various therapeutic approaches, including photodynamic therapy (PDT), targeted drug delivery, and hyperthermia therapy.39–41

1. **Photodynamic therapy (PDT) using AgNCs**

Photodynamic therapy involves the use of photosensitizing agents that, upon activation by light, produce reactive oxygen species that can selectively destroy cancer cells. When AgNCs are utilized as photosensitizers, their ability to generate ROS is harnessed, enabling efficient cancer cell eradication. This targeted approach minimizes damage to healthy tissues and holds promise for the treatment of various types of cancer.

2. **AgNC-assisted targeted drug delivery and controlled release**

AgNCs can act as carriers for anticancer drugs, enabling targeted drug delivery to tumor sites. By functionalizing the surface of AgNCs with specific ligands, they can selectively bind to cancer cells, thereby enhancing drug uptake and reducing the side effects on healthy tissues. Additionally, AgNCs can be engineered to effectively release the encapsulated drugs in response to specific triggers, such as pH changes or temperature variations. This controlled release mechanism ensures the desired therapeutic effects while minimizing systemic toxicity.

3. **Hyperthermia therapy: Harnessing AgNCs for tumor ablation**

Hyperthermia therapy involves the selective heating of tumor tissues to induce cell death. AgNCs can serve as efficient agents for hyperthermia therapy due to their excellent photothermal conversion efficiency. Laser irradiation can be used to excite the AgNCs, resulting in the conversion of light energy into heat, which leads to localized temperature elevation and subsequent tumor ablation. This approach holds promise as a non-invasive and targeted method for cancer treatment.[42]–[44]

## 6. Theranostic functions of AgNCs

### 6.1. Imaging-Guided Therapy

AgNCs have shown immense potential in guiding surgical procedures and monitoring treatment response in real-time. The following points highlight the impact of AgNCs in image-guided therapy:

1. **AgNCs in image-guided surgical procedures:**
   - AgNCs can be embedded in surgical tools or injected into the body to enhance surgical precision and accuracy.
   - By incorporating AgNCs into surgical instruments, surgeons can visualize real-time feedback and navigate through delicate tissues more effectively.
2. **Real-time monitoring of treatment response using AgNCs:**

- AgNCs can serve as contrast agents, enabling healthcare professionals to monitor the effectiveness of therapeutic interventions.
- By tracking the behavior of AgNCs in the body, medical practitioners can assess treatment response on a molecular level, making adjustments if necessary.

3. **Targeted therapy enabled by AgNC-based imaging feedback:**

- The capability of AgNCs to provide real-time imaging feedback allows for targeted and personalized therapy.
- By precisely analyzing the distribution of AgNCs within the body, healthcare providers can optimize treatment regimens and minimize side effects.[45]

### 6.2. AgNCs for Disease Diagnosis

AgNCs have also proven to be valuable tools in disease diagnosis due to their unique optical properties and high sensitivity. The following points highlight the importance of AgNCs in disease diagnosis:

1. **Detection and characterization of diseases using AgNCs:**

- AgNCs can be engineered to specifically bind to biomarkers associated with various diseases.
- By utilizing the optical properties of AgNCs, researchers can detect and characterize specific diseases with high sensitivity and accuracy.

2. **Early disease detection through AgNC-based diagnostic platforms:**

- AgNC-based diagnostic platforms offer the potential for early detection of diseases at a molecular level.
- The enhanced sensitivity of AgNCs enables the detection of disease biomarkers at very low concentrations, facilitating early intervention and improved patient outcomes.

3. **Point-of-care testing: AgNC biosensors for rapid and accurate diagnosis:**

- AgNC biosensors can be developed for point-of-care testing, enabling rapid and accurate diagnosis at the bedside or in resource-limited settings.
- The simplicity and cost-effectiveness of AgNC biosensors make them ideal for widespread deployment, particularly in areas lacking advanced healthcare infrastructure.[46], [47]

**Table 3: Theranostic applications of AgNCs**

| **Theragnostic Function** | **Description** |
|---|---|
| Cancer therapy | AgNCs can be used to target and kill cancer cells. They can also be used to deliver drugs or genes to cancer cells. |
| Antibacterial activity | AgNCs can kill bacteria, fungi, and other microorganisms. They can be used to prevent infection or to treat existing infections. |
| Antioxidant activity | AgNCs can scavenge free radicals and protect cells from damage. They can be used to treat diseases caused by oxidative stress, such as cancer and neurodegenerative diseases. |
| Anti-inflammatory activity | AgNCs can reduce inflammation. They can be used to treat diseases caused by inflammation, such as rheumatoid arthritis and asthma. |
| Anti-allergic activity | AgNCs can prevent allergic reactions. They can be used to treat allergies, such as hay fever and eczema. |

## 7. Challenges and future perspectives

The field of silver nanoclusters (AgNCs) has garnered significant attention in the realm of biomedical applications due to their unique properties and potential therapeutic benefits. However, several challenges and future perspectives need to be addressed in order to fully exploit their capabilities and ensure their safe implementation.

### 7.1. Toxicity and Biocompatibility

#### A. Investigating AgNC toxicity and potential adverse effects

One of the primary concerns surrounding the utilization of AgNCs in biomedical applications revolves around their toxicity and potential adverse effects on living organisms. Extensive research is required to comprehensively understand the interactions between AgNCs and biological systems. Studies examining the effects of various factors such as size, shape, surface coating, and concentration of AgNCs on cellular functions, DNA integrity, and organ systems are crucial to comprehensively evaluate their toxicity profile.[48]

### B.Strategies for enhancing the biocompatibility of AgNCs

To minimize potential toxicity, researchers are exploring strategies to enhance the biocompatibility of AgNCs. Surface modifications and functionalization techniques are being employed to improve the stability and reduce the cytotoxicity of AgNCs. By altering the surface properties, such as incorporating biocompatible polymers or encapsulating AgNCs within protective nanoparticles, it is possible to enhance their compatibility with biological systems without compromising their therapeutic efficacy.

### C. Regulatory considerations and safety guidelines for AgNC-based therapies

As AgNCs continue to make strides in biomedical applications, establishing regulatory considerations and safety guidelines is imperative. The development of standardized protocols for the synthesis, characterization, and administration of AgNCs is necessary to ensure the safety and efficacy of these novel therapies. Regulatory agencies must collaborate with researchers and industry experts to assess the potential risks, establish guidelines for clinical trials, and devise appropriate guidelines to address the ethical implications associated with the utilization of AgNCs in healthcare settings.[49]

## 7.2. Emerging Applications and Innovations

### A. AgNCs in stem cell research and tissue engineering

The unique properties of AgNCs make them promising tools for advancements in stem cell research and tissue engineering. AgNCs can act as enhancements to cellular differentiation, proliferation, and tissue regeneration processes. Their ability to modulate the behavior of stem cells and promote tissue repair makes them invaluable in the development of novel therapies for various degenerative disorders. Additionally, AgNCs can serve as carriers for targeted drug delivery systems, enabling precise therapeutic interventions and minimizing off-target effects.

### B. AgNCs in neurological disease diagnosis and therapy

Neurological diseases pose significant challenges in terms of accurate diagnosis and effective therapy. AgNCs hold great potential in revolutionizing these areas by providing novel diagnostic tools and targeted therapeutic approaches. Their unique optical properties, such as strong fluorescence, surface plasmon resonance, and size-dependent emission, allow for precise imaging and detection of neurological abnormalities. Furthermore, AgNCs can be functionalized to deliver therapeutic agents specifically to affected areas, providing a promising avenue for targeted drug delivery in the treatment of neurodegenerative disorders.[50]

### C. Nano-bio interfaces: AgNCs for enhancing human-machine interactions

AgNCs have the potential to revolutionize human-machine interactions by facilitating the development of nano-bio interfaces. These interfaces enable seamless communication and integration between biological entities and technological devices. AgNCs can serve as vital components in the fabrication of bioelectrodes and biosensors, offering high sensitivity, selectivity, and stability. Through the incorporation of AgNCs, advancements can be made in areas such as neural prosthetics, brain-computer interfaces, and wearable healthcare devices, leading to significant improvements in the quality of life for individuals with disabilities.

## CONCLUSION

In conclusion, silver nanoclusters (AgNCs) have emerged as transformative agents in the field of biomedicine, offering unique properties and diverse applications. The journey of AgNCs from their discovery to their current prominence in biomedical research and healthcare has been a remarkable one. Their small size, excellent optical properties, and biocompatibility have made them versatile tools in various biomedical domains. AgNCs have revolutionized bioimaging by enhancing the precision and sensitivity of cellular and tissue imaging. Their use as contrast agents and their ability to enable multimodal imaging have paved the way for deeper insights into complex biological processes. In vivo imaging with AgNCs has enabled real-time tracking and monitoring of systems within living organisms, facilitating advancements in regenerative medicine and drug delivery.

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