

# **GOLD NANOPARTICLES SYNTHESIS, CHARACTERIZATION TECHNIQUE AND APPLICATIONS**

## **Abstract**

Last 150 years, Gold Nanoparticles have proved significant advances gradually, including medical science, pharmacy & biological science. It leads with some medical & industrial applications like anticancer therapies, chemotherapies & in drug delivery. Nanotechnology involves multifunctionality, imaging, size distribution, therapeutic agents etc. Photothermal treatment can be applied to cancer with the help of gold nanoparticles. They can manage non-specific distribution areas & make infarction of only cancerous cells instead of making infarction cancerous as well as normal human cells. Tumours are the alloy of cancer cells as gold nanoparticles are featured with sub-micronic size so that they can penetrate tumours under some targeted drug delivery systems. Gold nanoparticles are perceptible, especially in cancer therapy, because of their remarkable compatibility & optical properties. In this journal, we are going to focus on recent developments in gold nanoparticle synthesis & its applications. So the applications of gold nanoparticles have some partial attention in chemical science as well, besides biomedical applications.

**Keywords:** Nanoparticle synthesis, Chemotherapy, GNP, Green synthesis, Drug delivery, Biomedical Applications

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## I. INTRODUCTION

**Nanotechnology and Nanomaterials:** Nanoscience and nanotechnology have become one of the trends of present day cutting edge research. The term has come from the latin term “Nanus” which mean very small. In dimension less than 100  $\mu\text{m}$  called nano. The introduction of the concept of nanotechnology historically first time was given by famous Physicist Dr. Richard Feynman in a lecture named as “There’s Plenty of Room at the Bottom” at the American Physical Society Meeting at Caltech on December 29, 1959. Feynman described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally small set and so on down to the needed scale. The term “Nanotechnology” was defined by Tokyo Science University Professor Nario Taniguchi in his paper. Nanotechnology mainly consists of the processing, separation, consolidation and deformation of materials by one atoms or by one molecules. Nanoparticles are minuscule particles with dimensions typically in the range of 1 to 100nm. At this scale, materials exhibit unique and novel properties distinct from their bulk counterparts. Nanotechnology refers to manipulating, fabricating, and applying these nanoparticles to create innovative materials, devices, and systems with exceptional functionalities.

Nanotechnology holds immense promise across various domains, including medicine, electronics, energy, and environmental science. In medicine, nanoparticles enable targeted drug delivery, improving treatment efficacy while reducing side effects. They also facilitate advanced diagnostic imaging, aiding in early disease detection. Nanotechnology contributes to faster, smaller, and more efficient devices in electronics, enhancing computing power and energy efficiency.

Moreover, nanotechnology finds applications in environmental remediation, where nanoparticles act as catalysts to degrade pollutants. It also enhances renewable energy technologies, such as solar and fuel cells, by improving efficiency.

However, the field of nanotechnology also poses a few challenges, such as potential toxicity and ethical considerations surrounding the use of nanomaterials. Despite these challenges, the ongoing advancements in nanotechnology hold the potential to revolutionize various industries, leading to a more sustainable and technologically advanced future.

## II. SIGNIFICANCE OF GOLD NANOPARTICLES

Gold nanoparticles (AuNPs) hold significant importance due to their unique properties and versatile applications across various fields. Their distinct physicochemical characteristics stem from their small size and high surface area-to-volume ratio, making them highly attractive for scientific and technological advancements.

Gold nanoparticles have shown immense promise in medicine as diagnostic tools and drug delivery carriers. Their ability to functionalize with specific targeting molecules allows them to deliver drugs directly to diseased cells, minimizing side effects and increasing treatment efficiency. Additionally, they are utilized in medical imaging, enhancing contrast for improved visualization of tissues and cells.

In the field of electronics, gold nanoparticles play a crucial role in developing miniaturized and efficient devices. They are utilized in conductive inks for printed electronics, enabling flexible and lightweight circuitry. Their unique optical properties, precisely surface plasmon resonance, have paved the way for advancements in sensors and detectors.

Furthermore, AuNPs find applications in catalysis, promoting chemical reactions with increased efficiency and selectivity. They are employed as catalysts in green chemistry, enabling environmentally friendly processes for various industrial applications.

In summary, the significance of gold nanoparticles lies in their diverse applications, ranging from targeted drug delivery and medical imaging to improving electronics and catalysis. As researchers continue exploring their potential, gold nanoparticles are poised to revolutionize numerous fields and contribute to advancing science and technology.

- 1. Synthesis Techniques:** Various researcher and scientist were encompass an in-depth analysis of various synthesis methods, including chemical, physical, and biological approaches, highlighting their pros and cons and discussing recent advancements in each technique.
- 2. Characterization Methods:** A thorough examination of characterization techniques used to assess the size, shape, and stability of GNPs, such as TEM, SEM, UV-Vis spectroscopy, DLS, and XRD, is essential for understanding their properties and potential applications
- 3. Functionalization and Surface Chemistry:** This aspect can explore how surface functionalization of GNPs influences their stability, biocompatibility, and targeted delivery, along with discussions on various ligands and coatings employed.
- 4. Biomedical Applications:** Focusing on drug delivery, photothermal therapy, imaging, and diagnostic applications of GNPs in the medical field, including their potential in precision medicine and personalized treatment.
- 5. Nanoelectronics and Sensors:** Exploring the potential of GNPs in nanoelectronics, sensors, and catalysis, and their impact on enhancing the performance of devices.
- 6. Future Perspectives:** The review can conclude with a discussion on the current challenges and prospects of GNPs synthesis and their application, proposing areas for further research and potential breakthroughs.

### III. DIFFERENTS TYPES OF GOLD NANOPARTICLES

Gold nanoparticles (AuNPs) come in various types based on their size, shape, and structure. The synthesis methods influence their characteristics, leading to a diverse range of gold nanoparticles with unique properties. Some common types of gold nanoparticles include:

- 1. Spherical Gold Nanoparticles:** Spherical AuNPs are the most basic and widely studied type. They have a uniform spherical shape and are usually synthesized using chemical methods, such as the Turkevich or Brust-Schiffrin methods. Spherical nanoparticles exhibit strong surface plasmon resonance (SPR) in the visible range, making them suitable for various applications, including biosensors, imaging, and catalysis.
- 2. Gold Nanorods:** Gold nanorods have an elongated shape, resembling small rods. The synthesis of nanorods involves the use of seed-mediated growth methods or template-assisted approaches. Their SPR can be tuned across visible and near-infrared regions, making them valuable for photothermal therapy, imaging, and other biomedical applications.
- 3. Gold Nanoshells:** Gold nanoshells consist of a dielectric core coated with a thin gold shell. The shell thickness and core material determine their optical properties, allowing precise control over SPR. Nanoshells find applications in cancer therapy, as they can be tuned to absorb light in the near-infrared region, enabling deep tissue penetration for photothermal ablation of cancer cells.
- 4. Gold Nanocages:** Gold nanocages are hollow structures with a porous surface of interconnected gold nanoparticles. They possess unique optical properties due to their open interior, making them suitable for imaging, drug delivery, and photothermal therapy.
- 5. Gold Nanostars:** Gold nanostars have multiple sharp branches protruding from a central core, resembling a star-like structure. The units contribute to a highly enhanced SPR effect, making nanostars excellent candidates for SERS and photothermal applications.
- 6. Gold Nanoclusters:** Gold nanoclusters are ultra-small nanoparticles composed of a few to a few dozen atoms. Due to their small size, they perform unique electronic and optical properties. They find applications in sensing, imaging, and as catalysts for specific reactions.
- 7. Gold Nanowires and Nanotubes:** Gold nanowires and nanotubes are elongated structures with varying diameters. They are interesting in electronics and sensor applications due to their unique electronic and optical properties and high aspect ratios.

#### IV. DIFFERENT METHODS OF GOLD NANOPARTICLE SYNTHESIS

- 1. Physical Methods:** Physical methods of gold nanoparticle synthesis involve the generation of nanoparticles through physical processes without the use of chemical reagents or biological agents. These methods offer precise control over nanoparticle size, shape, and purity, making them valuable for various applications. Some of the standard physical methods for gold nanoparticle synthesis include:
  - **Laser Ablation:** This method utilizes high-energy laser pulses focused on a gold target immersed in a liquid medium. The intense laser energy vaporizes the gold, leading to the formation of gold nanoparticles in the liquid. Laser ablation enables the production of well-defined nanoparticles with narrow size distributions.

- **Arc Discharge:** In this method, an electric arc is generated between two gold electrodes in an inert gas atmosphere. The high temperature and pressure cause gold atoms to vaporize and subsequently condense into nanoparticles. The arc discharge is commonly used to synthesize carbon-encapsulated gold nanoparticles.
  - **Sputtering:** Sputtering involves bombarding a gold target with high-energy ions, causing gold atoms to eject from the surface and deposit onto a substrate. The deposited gold atoms then aggregate and form nanoparticles. Sputtering is advantageous as it allows the synthesis of gold nanoparticles on various substrates, making it suitable for electronics and thin-film applications.
2. **Chemical Methods:** Chemical methods of gold nanoparticle synthesis are widely used due to their versatility, scalability, and precise control over nanoparticle size and shape. These methods involve reducing gold precursors to form nanoparticles using chemical reagents. Some of the standard chemical methods are:
- **Turkevich Method:** This classical method involves the reduction of gold ions (usually  $\text{HAuCl}_4$ ) in the presence of trisodium citrate as a reducing and stabilizing agent. The citrate ions reduce  $\text{Au(III)}$  ions to  $\text{Au(0)}$  atoms, forming stable spherical gold nanoparticles.
  - **Brust-Schiffrin Method:** This method utilizes a two-phase system involving the reduction of  $\text{Au(III)}$  ions by sodium borohydride in the presence of an organic phase. Alkanethiols act as ligands, controlling the nanoparticle size and providing stability.
  - **Seed-Mediated Growth:** This method involves two steps. First, small gold nanoparticles (seeds) are synthesized using a chemical reduction method. Then, these seeds act as nucleation sites for further growth by reducing additional gold precursors. This method allows control over size and shape, enabling the synthesis of anisotropic nanoparticles.
  - **Polyol Method:** This method utilizes polyols (such as ethylene glycol) as both reducing and stabilizing agents. In the presence of a metal salt precursor, polyols reduce the ions, forming nanoparticles. The addition of surfactants helps control particle size.
  - **Sol-Gel Method:** This method involves the formation of gold nanoparticles within a silica gel matrix. Gold precursors are mixed with a sol-gel solution and subsequent reduction results in the incorporation of nanoparticles into the gel network.
3. **Biological Methods:** Biological methods of gold nanoparticle synthesis, often called green synthesis, utilize natural biomolecules, such as proteins, enzymes, and plant extracts, as reducing and stabilizing agents. These eco-friendly approaches offer numerous advantages, including cost-effectiveness, biocompatibility, and ease of scalability.

- 4. Microorganisms-Mediated Synthesis:** Certain microorganisms, including bacteria and fungi, can reduce gold ions ( $\text{Au}^{3+}$ ) to elemental gold ( $\text{Au}^0$ ). This process involves the enzymatic activity of microorganisms that convert metal ions into nanoparticles. The choice of microorganisms and reaction conditions influence the size and shape of the resulting nanoparticles.
- 5. Plant Extracts as Reducing Agents:** Plants contain many bioactive compounds, such as polyphenols and flavonoids, which can effectively reduce  $\text{Au}^{3+}$  to  $\text{Au}^0$ . The extract from various plant parts, such as leaves, stems, or seeds, can be synthesized. Plant-mediated synthesis offers a green and sustainable approach, and the capping agents present in the extract provide stability to the formed nanoparticles.
- 6. Enzyme-Assisted Synthesis:** Enzymes, being biocatalysts, are highly efficient in reducing  $\text{Au}^{3+}$  ions and controlling the nucleation and growth of nanoparticles. Enzyme-assisted synthesis allows precise control over nanoparticle size and shape. Laccase, for instance, has been extensively used to synthesize gold nanoparticles.

## V. CHARACTERIZATION TECHNIQUES FOR GOLD NANOPARTICLES

Characterization techniques are essential for understanding the properties and behaviour of gold nanoparticles (AuNPs). Various methods are employed to analyze their size, shape, distribution, and surface properties. Below are some commonly used characterization techniques for gold nanoparticles:

- 1. Transmission Electron Microscopy (TEM):** TEM provides high-resolution images of nanoparticles, enabling direct observation of their size and morphology. It allows researchers to determine the shape of individual particles and assess their uniformity and dispersion.
- 2. Scanning Electron Microscopy (SEM):** SEM is useful for imaging the surface topography of gold nanoparticles. Unlike TEM, which requires thin sample preparation, SEM can analyze bulkier samples and provide information about particle size and distribution on a larger scale.
- 3. UV-Visible Spectroscopy:** UV-Visible spectroscopy measures light absorption by gold nanoparticles in the visible region. The absorption peak corresponds to the surface plasmon resonance (SPR) of the nanoparticles, which is influenced by their size and shape. This technique is widely used for rapid qualitative analysis and estimation of nanoparticle concentration.
- 4. Dynamic Light Scattering (DLS):** DLS determines the hydrodynamic size distribution of nanoparticles in a solution by analyzing the fluctuations in light scattering caused by Brownian motion. It provides information about the particle size in the dispersed state, including agglomerates or aggregates.
- 5. X-ray Diffraction (XRD):** XRD is used to identify the crystal structure of gold nanoparticles. The diffraction pattern generated by X-rays interacting with the nanoparticles provides information about their lattice parameters and crystal phase.

- 6. Fourier Transform Infrared Spectroscopy (FTIR):** FTIR measures the vibrations of functional groups on the nanoparticle surface, providing information about capping agents or stabilizing molecules. This helps to understand the gold nanoparticles' surface chemistry and potential functionalization.

These characterization techniques collectively contribute to a comprehensive understanding of gold nanoparticles, facilitating their optimization for specific applications in medicine, electronics, catalysis, and other fields.

## VI. PHYSIOCHEMICAL PROPERTIES OF GOLD NANOPARTICLES

Gold nanoparticles (AuNPs) possess unique physicochemical properties, making them highly attractive for various applications. These properties are a result of their nanoscale size and specific surface characteristics. Some of the key physicochemical properties of gold nanoparticles include:

- 1. Size and Shape Dependent Properties:** The size and shape of AuNPs significantly influence their properties. As the size decreases, the surface-to-volume ratio increases, enhancing reactivity and unique optical properties. AuNPs of different shapes, such as spheres, rods, and triangles, exhibit distinct plasmonic resonances, affecting their absorption and scattering of light.
- 2. Surface Plasmon Resonance (SPR):** One of the most remarkable properties of AuNPs is their ability to support surface plasmon resonance. When exposed to light, the collective oscillation of free electrons on the nanoparticle's surface generates a localized solid electromagnetic field, resulting in enhanced absorption and scattering of light. This property finds applications in various areas, including sensors, imaging, and photothermal therapy.
- 3. Stability and Aggregation Behavior:** AuNPs can exhibit different stability profiles based on their surface functionalization and surrounding environment. Surface modifications with ligands or stabilizing agents prevent aggregation and enhance colloidal stability. However, in certain conditions, such as changes in pH or ionic strength, AuNPs may undergo aggregation, which impacts their properties and applications.
- 4. Surface Functionalization:** The surface of AuNPs can be easily functionalized with various molecules, such as thiol-containing ligands, polymers, or biomolecules. This functionalization imparts new properties and functionalities to the nanoparticles, allowing them to be tailored for specific applications, including drug delivery, bioimaging, and catalysis.

In summary, the physicochemical properties of gold nanoparticles, including size and shape-dependent features, surface plasmon resonance, stability, and biocompatibility, contribute to their widespread applications in medicine, electronics, catalysis, and many other fields. The ability to tune these properties offers tremendous potential for further innovation and advancement in nanotechnology.

## VII. FUNCTIONALIZATION OF GOLD NANOPARTICLES

Functionalizing gold nanoparticles (AuNPs) involves modifying their surface with various molecules, such as ligands, polymers, biomolecules, or other nanoparticles. This process imparts specific properties and functionalities to the AuNPs, enabling their use in various applications. Some standard methods of functionalizing gold nanoparticles include:

- 1. Thiol-Based Functionalization:** One of the most widely used methods involves attaching thiol-containing molecules, such as thiolated ligands or thiol-modified polymers, onto the gold nanoparticle surface. This forms a robust gold-sulfur bond, creating a self-assembled monolayer that stabilizes the nanoparticles and provides functional groups for further modifications [5,6,15].
- 2. Polymer Coating:** Polymer functionalization involves coating gold nanoparticles with various polymers, such as polyethylene glycol (PEG), polyvinylpyrrolidone (PVP), or polyacrylic acid (PAA). Polymer coatings enhance nanoparticle stability, improve biocompatibility, and enable the attachment of specific targeting ligands for biomedical applications.
- 3. Biomolecule Conjugation:** Gold nanoparticles can be functionalized with biomolecules, such as antibodies, peptides, DNA, or enzymes. These biomolecules can be attached to the AuNPs' surface via covalent bonding or non-covalent interactions. This functionalization enables targeted drug delivery, bioimaging, and biosensing applications [9].
- 4. Click Chemistry:** Click chemistry is a powerful method for attaching molecules to gold nanoparticles with high specificity and efficiency. Reactions like azide-alkyne cycloaddition or thiol-maleimide coupling can be employed to functionalize the nanoparticles with a wide range of molecules.
- 5. Core-Shell Functionalization:** Core-shell functionalization involves encapsulating gold nanoparticles with a secondary material, such as silica, polymers, or other metal oxides. This dual-layer structure provides additional functionalities and protects the gold core, expanding its drug delivery and imaging applications.
- 6. Magnetic Functionalization:** Magnetic functionality can be introduced by incorporating magnetic nanoparticles into the AuNPs. These magnetic gold nanoparticles find use in targeted drug delivery, magnetic hyperthermia, and as contrast agents in magnetic resonance imaging (MRI).

## VIII. APPLICATIONS OF GOLD NANOPARTICLES

Gold nanoparticles (AuNPs) have found numerous applications across various fields due to their unique properties and ease of functionalization. Some of the major applications of gold nanoparticles include:



## 1. Biomedical Applications

- **Drug Delivery:** AuNPs can be functionalized with drugs and targeted to specific tissues, allowing controlled and targeted drug delivery. Drug delivery improves treatment efficacy and reduces side effects.
- **Imaging:** Gold nanoparticles serve as contrast agents in various imaging modalities, such as X-ray, computed tomography (CT), and photoacoustic imaging, enhancing image resolution and sensitivity.
- **Biosensing:** AuNPs are used in diagnostic biosensors to detect biomolecules, pathogens, or disease markers with high sensitivity and specificity.
- **Photothermal Therapy:** Gold nanoparticles can absorb near-infrared light and convert it into heat, enabling localized photothermal therapy for cancer treatment.

## 2. Electronics and Photonics

- **Conductive Inks:** Gold nanoparticles are used in transmittable inks for printed electronics, enabling flexible and lightweight circuits.
- **Nanoelectronics:** AuNPs find applications in electronic devices, such as transistors and memory, due to their unique electronic properties.
- **Surface-Enhanced Raman Scattering (SERS):** Gold nanoparticles act as substrates to enhance the Raman signal of nearby molecules, making them valuable for ultrasensitive molecular detection.

## 3. Catalysis

- **Homogeneous Catalysis:** Gold nanoparticles act as catalysts in various chemical reactions, including oxidation and reduction processes.
- **Heterogeneous Catalysis:** Supported gold nanoparticles serve as catalysts in industrial processes, such as hydrogenation and carbon monoxide oxidation.

## 4. Environmental Applications

- **Water Purification:** AuNPs functionalized with specific molecules can remove pollutants, heavy metals, and organic contaminants from water.
- **Detection of Environmental Pollutants:** Gold nanoparticles are sensors to detect environmental pollutants and toxins.
- **Remediation of Contaminated Sites:** AuNPs aid in the remediation of contaminated sites by catalyzing the degradation of contaminants.

## 5. Nanomedicine

- **Photodynamic Therapy (PDT):** AuNPs can enhance photodynamic therapy by increasing the efficiency of light-induced reactive oxygen species production for cancer treatment.
- **Gene Delivery:** Functionalized gold nanoparticles can deliver genes into cells, enabling gene therapy for various genetic disorders.

## IX. APPLICATIONS OF GOLD NANOPARTICLES FOR DRUG DELIVERY

Gold nanoparticles (AuNPs) have found numerous applications across various fields due to their unique properties and ease of functionalization. Some of the major applications of gold nanoparticles include:

### 1. Biomedical Applications

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- **Photothermal Therapy:** Gold nanoparticles can absorb near-infrared light and convert it into heat, enabling localized photothermal therapy for cancer treatment [7,8,14].

### 2. Electronics and Photonics

- **Conductive Inks:** Gold nanoparticles are used in transmittible inks for printed electronics, enabling flexible and lightweight circuits.
- **Nanoelectronics:** AuNPs find applications in electronic devices, such as transistors and memory, due to their unique electronic properties.
- **Surface-Enhanced Raman Scattering (SERS):** Gold nanoparticles act as substrates to enhance the Raman signal of nearby molecules, making them valuable for ultrasensitive molecular detection [1,3,4].

### 3. Catalysis

- **Homogeneous Catalysis:** Gold nanoparticles act as catalysts in various chemical reactions, including oxidation and reduction processes. Heterogeneous Catalysis:

Supported gold nanoparticles serve as catalysts in industrial processes, such as hydrogenation and carbon monoxide oxidation.

#### 4. Environmental Applications

- **Water Purification:** AuNPs functionalized with specific molecules can remove pollutants, heavy metals, and organic contaminants from water.
- **Detection of Environmental Pollutants:** Gold nanoparticles are sensors to detect environmental pollutants and toxins.
- **Remediation of Contaminated Sites:** AuNPs aid in the remediation of contaminated sites by catalyzing the degradation of contaminants [2].

#### 5. Nanomedicine

- **Photodynamic Therapy (PDT):** AuNPs can enhance photodynamic therapy by increasing the efficiency of light-induced reactive oxygen species production for cancer treatment.
- **Gene Delivery:** Functionalized gold nanoparticles can deliver genes into cells, enabling gene therapy for various genetic disorders.

#### 6. Food Industry

- **Food Safety:** Gold nanoparticles are sensors for detecting food products' pathogens and contaminants.
- **Food Packaging:** AuNPs improve the barrier properties of food packaging materials, extending the shelf life of perishable products.

### X. IN-VIVO TARGETING BY USING GOLD NANOPARTICLES

In-vivo targeting using gold nanoparticles (GNPs) is a promising strategy in nanomedicine for precise drug delivery and diagnostic applications. GNPs possess unique properties that make them attractive candidates for targeted therapy:

1. **Active Targeting:** GNPs can be functionalized with specific ligands or antibodies that recognize and bind to overexpressed receptors or biomarkers on the surface of target cells, such as cancer cells. This active targeting approach allows for the selective accumulation of GNPs at the desired site, increasing drug concentration and reducing side effects [10].
2. **Passive Targeting (Enhanced Permeability and Retention Effect):** GNPs can exploit tumour tissues' enhanced permeability and retention (EPR) effect. Due to their small size, GNPs can accumulate in tumour vasculature through leaky blood vessels and stay localized in the tumour environment, enhancing drug delivery efficiency.

- 3. Biocompatibility:** Carefully engineered GNPs exhibit excellent biocompatibility, minimizing potential toxicity concerns and enabling safe use in living organisms.
- 4. Image-Guided Targeting:** GNPs possess intense light scattering properties, allowing for photoacoustic and photothermal imaging. This imaging capability aids in real-time monitoring of GNP distribution and targeted drug delivery.
- 5. Multimodal Therapy:** GNPs can be utilized for drug delivery and other therapeutic modalities like photothermal therapy (PTT) and photodynamic therapy (PDT). PTT uses the photothermal effect of GNPs to generate localized heat and destroy tumour cells, while PDT involves developing reactive oxygen species upon light exposure to kill cancer cells [11-13,16].
- 6. Reduced Drug Resistance:** Targeted drug delivery using GNPs can overcome drug resistance often observed in conventional therapies, as it improves drug concentration at the target site [17].
- 7. Personalized Medicine:** GNPs can be tailored with specific surface coatings and functional groups to suit individual patient needs, supporting the advancement of personalized medicine approaches.

## XI. CONCLUSION

Gold nanoparticle (GNPs) synthesis has advanced significantly, offering versatile applications in various fields. Their fabrication can be achieved through multiple methods, such as chemical, physical, and biological routes. GNPs are used extensively in medicine, acting as efficient drug delivery carriers, targeted imaging agents, and therapeutic tools for cancer treatment (e.g., photothermal and photodynamic therapy). In electronics, GNPs enhance sensor sensitivity and offer potential in nanoelectronics. Their catalytic properties have environmental applications for pollutant degradation. GNPs' unique optical and plasmonic properties lead to advancements in sensing and imaging technologies. GNPs' synthesis and applications drive innovation across multiple disciplines, holding great promise for future developments.

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