International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

A Comprehensive Review on Gold Nanoparticles

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ABSTRACT:

Gold nanoparticles are minute particles having a size ranging from 1to 100 nano meters in size.They are more stable and Non toxic and they are easy to synthesize .because of its unique properties and behaviour like surface plasmon reasonance enables the particles to absorb and scatter the light which can be used for medical and diagnostic purpose.they acts as carriers for drug molecules and also for transport o large biomolecules like DN and RNA Additionally it can be used in cancer treatment.they can be synthesised by physical, chemical and green synthesis methods. There are different types of gold nanoparticles based on their size and shape.

Keywords: Gold Nanoparticles, Surface Plasmon Reasonance, Cancer Treatment, Brust Method, Schriffin Method, Targeted drug delivery, Controlled Drug Release, Imaging and Biosensing

1. INTRODUCTION:

Gold nanoparticles (AuNPs) have gained significant attention in recent years due to their remarkable physical, chemical, and optical properties. These nanoparticles, typically ranging from 1 to 100 nano meters in size, exhibit characteristics that differ greatly from bulk gold. Their unique behaviour arises mainly from their high surface-area-to-volume ratio and surface plasmon resonance (SPR), which gives them distinct and vibrant colours along with exceptional optical features.

The properties of gold nanoparticles make them highly versatile. Their surface plasmon resonance (SPR) enables strong light absorption and scattering, while their high surface area enhances reactivity and interaction with other molecules. They are also biocompatible, making them safe for medical use, and their chemical stability ensures resistance to oxidation and corrosion. Additionally, their surface can be functionalized with biomolecules, drugs, or polymers for targeted applications.

Because of these properties, gold nanoparticles are widely used across various fields. In medical diagnostics, they play a crucial role in biosensors and rapid disease detection kits. They are employed in drug delivery systems to transport and release therapeutic agents precisely. In cancer treatment, gold nanoparticles are used in photothermal therapy, where they convert light into heat to selectively destroy cancer cells. They also enhance imaging techniques, serve as efficient catalysts in chemical reactions, and contribute to environmental applications like water purification and pollutant detection.

With their unique properties and broad range of applications, gold nanoparticles continue to drive innovation in medical, industrial, and environmental sectors, making them a vital part of nanotechnology research and development.[1]

2. Properties of Gold Nanoparticles

2.1 Surface Plasmon Resonance (SPR):

This is the most important optical property of gold nanoparticles. When light hits the particles, the free electrons on their surface start oscillating in sync with the light’s electromagnetic field. This collective oscillation results in strong absorption and scattering of light at specific wavelengths, giving gold nanoparticles their intense, size-dependent colours.this can be helpful in colometric sensing and photo thermal theraphy.

2.2 Size-Dependent Optical Behaviour:

The optical properties of GNPs change with their size:

- **Smaller particles (10-20 nm):** They mainly absorb light and appear red.

- **Larger particles (50-100 nm):** They start scattering more light and shift toward blue or purple.As the particle size increases, the SPR peak moves toward longer wavelengths (red-shifted).

2.3 Shape-Dependent Optical Properties:

The shape of gold nanoparticles greatly influences how they interact with light

- **Spherical GNPs:** Show a single SPR peak.
- **Gold nanorods:** Exhibit two SPR peaks — one for the shorter transverse axis and one for the longer longitudinal axis.
- **Gold nano stars or nano shells:** Display multiple resonance peaks due to their complex shapes.

These shape variations allow precise tuning of their optical response.

2.4 Localized Surface Plasmon Effect:

Near the surface of gold nanoparticles, the electric field gets highly intensified due to SPR. This localized enhancement is used in techniques like surface-enhanced Raman scattering (SERS), allowing the detection of even minute quantities of chemical species.this can be used in imaging and sensing.

2.5 High Photostability:

Unlike traditional fluorescent dyes, gold nanoparticles don’t easily degrade or lose their brightness when exposed to light, making them ideal for long-term imaging and labelling.[2]

3. Synthesis methods of gold nanoparticles

3.1 Chemical Methods

Turkevich Method

The Turkevich method, established in 1951, remains one of the most widely adopted techniques for synthesizing spherical gold nanoparticles. This method involves the reduction of chloroauric acid ($HAuCl_4$) with trisodium citrates, amino acids, ascorbic acid in an aqueous medium. The citrate ions serve a dual role as both a reducing agent and a stabilizer, preventing particle aggregation. The resultant nanoparticles typically size ranging from 1to2 nm, with reaction conditions influencing size and dispersity.[3]

Brust-Schiffrin Method

The Brust-Schiffrin two-phase method enables the synthesis of Alkane thiol-stabilized gold nanoparticles with diameters between 1.5 to 5 nm,by biphasic reduction protocol. In this approach, an aqueous solution of Chloro Auric Acid ($HAuCl_4$) is transferred into an organic phase using a phase transfer reagent like Tetra Octyl Ammonium Bromide (TOAB). Sodium borohydride ($NaBH_4$) serves as a strong reducing agent, yielding highly stable nanoparticles. This method is particularly valued for producing monodispersed and functionalized nanoparticles suitable for organic applications.[3]

Seed-Mediated Growth

The first two method can synthesise only spherical AuNp.this method is commonly used for preparation rod shaped AuNp. This technique involves the initial formation of small seeded gold nanoparticles by $NaBH_4$, followed by their introduction into a growth solution containing additional gold salt and a mild reducing agent like Ascorbic acid this prevents the over nucleation and speed up the synthesis of AuNps.seeded growth method is useful in production of gold nanorods[12]. By carefully controlling the concentration and reaction environment, diverse morphologies such as nanorods, nanostars, and nanoplates can be synthesized. This method provides excellent control over particle shape and size.[3]

3.2 Physical Methods

Photochemical Synthesis

In photochemical synthesis, light irradiation induces the reduction of gold ions, leading to nanoparticle formation. This method often employs UV or visible light sources and photosensitive reducing agents. The advantages of this technique include high spatial control and the potential for creating patterned nanostructures.

Electrochemical Synthesis

Electrochemical methods involve the reduction of gold ions at the electrode surface through the application of an electric current. This approach enables precise control over nanoparticle size by adjusting voltage, current density, and electrolyte composition. Electrochemical synthesis is highly efficient and scalable, making it suitable for industrial applications.

Microwave-Assisted Synthesis

Microwave irradiation provides rapid and uniform heating, facilitating the quick formation of gold nanoparticles. This technique reduces reaction time while ensuring consistent particle size distribution, making it an efficient alternative to conventional heating methods.

3.3 Biological Methods

Green Synthesis

Biological synthesis employs plant extracts, microorganisms, or biomolecules to reduce gold ions, forming nanoparticles in an environmentally sustainable manner. This method avoids toxic chemicals, offering biocompatible and eco-friendly nanoparticles, low cost, higher reproducibility with potential biomedical applications**.** alkaloids, flavonoids, aminoacids, vitamins, ketones if any of the chemicals present in the plant composition these helps to reduce the gold particles. Microorganisms like algae, fungi, bacteria they reduce the gold particles [4].

Synthesis of Gold Nanoparticles by Plant Extracts:

Callus Induction

Hypocotyl segments from one-week-old seedlings germinated on water agar were excised and cultured on Murashige and Skoog (MS) medium (pH 5.7) supplemented with 30% sucrose, 0.8% agar, 0.2 mg/L indole-3-acetic acid (IAA), and 0.2 mg/L benzyladenine (BA). Explants were maintained for two weeks to induce callus formation.

Establishment of Suspension Culture

The developed callus tissues were transferred into liquid MS medium of the same composition. Cultures were maintained in 250 ml conical flasks on an orbital shaker at 100 rpm and 27 °C for 48 h. The resulting suspension cultures were examined microscopically to confirm the presence of single, free-floating cells .

Synthesis of Gold Nanoparticles

For nanoparticle synthesis, suspension cultures were supplemented with $KAuCl_4$ at concentrations ranging from 10–200 ppm and incubated in the dark on an orbital shaker for 24 h. The transformation of the medium color from pale yellow to ruby red served as a visual indicator of gold nanoparticle formation.

Purification of Nanoparticles

Aliquots (1 ml) of the treated cultures were transferred into Eppendorf tubes and centrifuged at 14,000 rpm for 2 min. The pellet was washed several times with nanopore water to remove traces of culture medium and unreacted gold. The washed cells were resuspended in 100 µL of nanopore water and lysed using a sonicator for 2 min to release the nanoparticles.[4]

SYNTHESIS OF GOLD NANOPARTICLES BY MICROORGANISMS:

Gold nanoparticles can be synthesised using micro-organisms either inside (intracellular) or outside (extracellular) the cells. The extracellular method is preferred since it avoids complex recovery steps. In this process, the culture is grown for 1–2 days, centrifuged, and the supernatant is mixed with a gold salt solution. A colour change from **ruby red to deep purple** confirms nanoparticle formation. This eco-friendly method is fast and similar to plant-mediated synthesis.[10]

4.TYPES OF GOLD NANOPARTICLES:

There are different types of gold nanoparticles based on their shapes. each shape have its own specificity of function because of their unique properties and their size.by using the above physical, chemical, biological methods we can synthesise this gold nanoparticles. there are different types of shapes such as nanorods, nanostars, nanocage, nanoclusters, nanospheres. [4]. [13], [9]

Shape	size	Applications
Nano Rod	2-5nm	Drug delivery and photothermal therapy.
Nano cube	50nm	Bioimaging and Biosensing
Nano cage	50nm	Used in endomicroscopy imaging
Nano belt	80nm	Strain sensors
Nano cluster	2-3nm	Bioimaging and Biosensing

5.CELLULAR UPTAKE OF GOLD NANOPARTICLES:

Gold nanoparticles (AuNPs) usually enter cells through endocytosis, most often by clathrin- or caveolae-mediated pathways, while larger ones can get in through macro pinocytosis or phagocytosis. Their size plays a big role: particles around 40–60 nm are taken up best, very tiny ones (<3 nm) can slip through membranes but are cleared quickly, and bigger ones (>100 nm) don't get in easily. Shape also matters—spheres and triangles are taken up more easily than rods or stars because the cell membrane can wrap around them more smoothly. Surface charge is another key factor: positively charged nanoparticles stick well to the negatively charged cell surface, while neutral or negatively charged ones usually need targeting molecules. By adding ligands like antibodies or peptides, scientists can guide nanoparticles into cells via receptor-mediated uptake, while PEGylation helps them stay longer in the bloodstream but reduces random uptake. Once inside, AuNPs usually end up in endosomes and lysosomes, unless they are specially coated to escape into the cytoplasm or nucleus. Overall, how well AuNPs get into cells depends on a mix of their properties and the cell's mechanisms, so careful design is crucial for their use in drug delivery, imaging, and therapy.[8]

6.APPLICATIONS :

Gold nanoparticles (AuNPs) are tiny gold particles that have amazing uses in medicine. They are widely used in drug delivery, imaging and diagnostics, and cancer therapy because of their unique properties. These particles are biocompatible, easy to modify, and have special optical features that make them useful in different medical applications.

6.1 Drug Delivery:

Gold nanoparticles act as tiny carriers that help deliver Biomolecules and medicines exactly where they are needed. This reduces side effects and makes treatments more effective.

- **Targeted Drug Delivery:** Scientists attach specific molecules like antibodies or peptides to AuNPs. These molecules help the nanoparticles find and enter diseased cells, such as cancer cells, while leaving healthy cells unharmed.
- **Controlled Drug Release:** Some medicines must be released at the right time. Gold nanoparticles can be designed to release drugs only when triggered by pH changes, heat, or light inside the body.
- **Gene Delivery:** Certain diseases require genetic treatment. AuNPs help in carrying DNA, RNA, or small interfering RNA (siRNA) into cells, which can help correct genetic disorders or stop harmful gene activity.[6]

6.2 Imaging and Diagnostics

Doctors need clear images of tissues and organs to detect diseases early. Gold nanoparticles improve medical imaging and make diagnostic tests more precise.

- **Enhanced Imaging:** In techniques like CT scans and fluorescence **imaging**, AuNPs provide better contrast, making tumours or infections easier to detect.
- **Biosensors for Disease Detection:** Rapid tests, like pregnancy kits or COVID-19 tests, use gold nanoparticles. When the sample reacts with AuNPs, a color change occurs, indicating the test result. This method can also detect the Mycobacterium tuberculosis, the causative agent of human tuberculosis in clinical samples.[11]
- **Raman Spectroscopy for Biomarker Detection:** Gold nanoparticles amplify signals in Surface-Enhanced Raman Spectroscopy (SERS). This helps detect diseases like cancer at very early stages by identifying biomarkers in blood samples.[5]

6.3 Cancer Therapy

Gold nanoparticles are changing how we treat cancer. They can kill cancer cells without harming healthy ones.

- **Photothermal Therapy (PTT):** When exposed to near-infrared (NIR) light, AuNPs heat up and destroy cancer cells without affecting nearby healthy tissues. This method is minimally invasive and highly targeted.
- **Photodynamic Therapy (PDT):** Some gold nanoparticles are designed to produce reactive oxygen species (ROS) when exposed to light. These ROS damage cancer cells and help kill them.
- **Chemotherapy Enhancement:** Traditional chemotherapy drugs can harm both cancerous and healthy cells, leading to severe side effects. By attaching these drugs to gold nanoparticles, scientists can directly deliver them to tumors, reducing harmful effects.[5] [9]

Gold nanoparticles are revolutionizing medicine. They make treatments safer, more effective, and highly targeted. As research continues, we may soon see even better ways to use these tiny particles in healthcare.

6.4 Gold nanoparticles (AuNPs) in environmental protection:

Biological synthesis employs plant extracts, microorganisms, or biomolecules to reduce gold ions, forming nanoparticles in an environmentally sustainable manner. This method avoids toxic chemicals, offering biocompatible and eco-friendly nanoparticles, low cost, higher reproducibility with potential biomedical applications**.** alkaloids, flavonoids, aminoacids, vitamins, ketones if any of the chemicals present in the plant composition these helps to reduce the gold particles. Microorganisms like algae, fungi, bacteria they reduce the gold particles.[3],[13]

1. Water Purification

- **Removing Toxic Metals**: Gold nanoparticles attract and capture heavy metals like lead and mercury.
- **Breaking Down Pollutants**: They speed up the degradation of harmful chemicals and dyes.
- **Cleaning Oil Spills**: Special coatings allow them to absorb oil while leaving water behind.

2. Pollution Detection

- **Water Testing**: Gold nanoparticles change color when exposed to heavy metals.
- **Air Quality Monitoring**: Sensors with gold nanoparticles detect harmful gases like carbon monoxide.
- **Soil Contamination Checks**: Portable sensors identify pesticides and industrial chemicals.

3. **Green Chemistry & Clean Energy**

- **Converting Pollutants**: Gold nanoparticles break down industrial waste into harmless byproducts.
- **Hydrogen Fuel Production**: They help extract hydrogen from water as a clean energy source.
- **Reducing CO_2 Emissions**: They convert carbon dioxide into useful fuels, reducing pollution.

4. **Environmental Remediation**

- **Boosting Bacteria for Cleanup**: Gold nanoparticles enhance bacteria that break down toxic waste.
- **Improving Water Filtration**: They make filters more effective in removing bacteria and virus.

7. Toxicity of gold nanoparticles:

Cellular Toxicity – AuNPs can cause oxidative stress, inflammation, and apoptosis (cell death) in certain cells, depending on their size, shape, and surface coating.

- **DNA Damage** – Studies suggest that AuNPs can interfere with genetic material, potentially leading to mutations.
- **Neurotoxicity** – Some evidence indicates that gold nanoparticles can cross the blood-brain barrier, potentially affecting brain function and causing neuroinflammation.
- **Immune System Disruption** – AuNPs may trigger immune responses, leading to allergies or immune suppression.
- **Accumulation in Organs** – Once inside the body, AuNPs tend to accumulate in the liver, kidneys, and spleen, which could lead to long-term toxicity.[13], [7]

8. Disadvantages of Gold Nanoparticles

1. **High Cost** – Producing gold nanoparticles is expensive, limiting their large-scale applications.
2. **Stability Issues** – AuNPs can aggregate, losing their unique properties and effectiveness in certain applications.
3. **Difficult Clearance from the Body** – Unlike other nanoparticles, AuNPs are not easily excreted and can persist in the body for long periods.
4. **Limited Biodegradability** – Unlike organic nanoparticles, gold does not degrade easily, raising concerns about long-term exposure effects.
5. **Toxicity Variability** – The toxicity of AuNPs depends on size, shape, surface charge, and coating, making risk assessment complex.
6. **Regulatory Hurdles** – Due to safety concerns, regulatory approval for medical and cosmetic use can be difficult and time-consuming.

9. Conclusion

Gold nanoparticles are very minute particles with special properties like surface plasmon reasonance, optical properties and their compatbility makes them useful in many fields. They are widely used in medicine for diagnosing diseases, delivering drugs, and even treating cancer. In electronics, they help in making smaller and more efficient devices. They are also used in environmental science for water purification and detecting pollutants.

One of their biggest advantages is that they can be easily modified to suit different needs. Their small size allows them to interact with cells in the human body, making them valuable in healthcare. However, there are still some challenges, such as their high cost, stability issues, and concerns about their long-term effects on health and the environment.

Despite these challenges, scientists continue to explore new ways to improve and use gold nanoparticles. As research advances, they are expected to become even more important in medicine, technology, and industry, improving many aspects of our daily lives.

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