IJRAR.ORG E-ISSN: 2348-1269, P-ISSN: 2349-5138

INTERNATIONAL JOURNAL OF RESEARCH AND ANALYTICAL REVIEWS (IJRAR) | IJRAR.ORG

An International Open Access, Peer-reviewed, Refereed Journal

Harnessing the Power of Gold Nanoparticles for Advanced Applications

Soumitra Mandal

Assistant Professor, Department of Chemistry, Fakir Chand College, Diamond Harbour-743331, South 24-Parganas, West Bengal, India

Abstract: Gold nanoparticles (AuNPs) have emerged as crucial nanomaterials, showcasing unparalleled properties that render them highly promising across diverse scientific domains. This paper offers an extensive exploration of AuNPs, focusing on their synthesis, characterization, and multifaceted applications. The fundamental ideas that govern the behaviour of AuNPs are discussed, with a focus on the significance of size and shape. Investigation is conducted on the synthesis techniques, which include template-assisted approaches, green synthesis, and conventional chemical reduction. The pivotal role of characterization techniques such as transmission electron microscopy (TEM), UV-Vis spectroscopy, and dynamic light scattering (DLS) in elucidating and optimizing nanoparticle properties is underscored.

Moving beyond the foundational aspects, the paper delves into the diverse applications of gold nanoparticles. In medicine, AuNPs exhibit extraordinary potential in drug delivery, imaging, and diagnostics, leveraging their ability to selectively target cells and tissues. The synergistic therapeutic effects, such as photothermal and photodynamic therapy, are explored, demonstrating the transformative impact of AuNPs in the medical arena. In the realm of electronics and catalysis, the electronic properties of AuNPs are harnessed to enhance the performance of electronic devices and catalysed chemical reactions with exceptional efficiency. Applications in sensors and renewable energy further underscore the versatility of gold nanoparticles.

While celebrating the potential of AuNPs, the paper acknowledges existing challenges, including concerns related to toxicity, scalability, and environmental impact. These challenges prompt a discussion on the need for responsible research practices and the exploration of eco-friendly synthesis methods. The paper concludes by presenting future perspectives that focus on overcoming current limitations and expanding the horizons of gold nanoparticle applications. The interdisciplinary nature of AuNP research is underscored, advocating for collaborative efforts to address challenges and propel innovation forward.

In essence, this paper serves as a comprehensive guide to understanding and harnessing the power of gold nanoparticles, shedding light on their synthesis, properties, and applications. It provides a roadmap for researchers and practitioners interested in leveraging the unique characteristics of AuNPs for advancements in medicine, electronics, catalysis, and beyond.

Keywords: Gold nanoparticles, Nanomaterials, Biomedical applications, photothermal and photodynamic therapy, electronics and catalysis.

1. Introduction

Gold nanoparticles (AuNPs) have emerged as captivating nanomaterials with exceptional properties, propelling them to the forefront of scientific research and technological innovation. At the nanoscale (typically ranging in size from 1 to 100 nanometers), gold exhibits unique physical, chemical, and optical characteristics that distinguish it from its bulk counterpart. These distinctive properties, coupled with the ability to precisely control the size and shape of nanoparticles, render AuNPs highly versatile and suitable for a myriad of advanced applications across diverse disciplines properties (Boisselier & Astruc, 2009; Dykman & Khlebtsov, 2011; Hu et al., 2020; Milan et al., 2022; Saleh & Hassan, 2023; Yeh et al., 2012).

The advent of nanotechnology has revolutionized our understanding of materials at the nanoscale, offering unprecedented opportunities to engineer materials with tailored properties for specific applications (Díez et al., 2022; Malik, Muhammad, et al., 2023; Malik, Singh, et al., 2023; Sim & Wong, 2021). Among nanomaterials, gold nanoparticles stand out for their remarkable attributes, making them a subject of intense investigation and exploration. Researchers are continually pushing the boundaries of AuNP synthesis, characterization, and application, seeking to unlock their full potential in various scientific and technological realms (Hu et al., 2020; Kumar et al., 2011; Milan et al., 2022).

As we embark on this exploration of gold nanoparticles, it is essential to recognize the interdisciplinary nature of this research endeavour. Collaborative efforts across various scientific disciplines, including chemistry, physics, biology, and materials science, are crucial for advancing our understanding and harnessing the power of AuNPs effectively. Moreover, while celebrating the tremendous opportunities afforded by gold nanoparticles, it is imperative to acknowledge and address existing challenges, such as concerns related to toxicity, scalability, and environmental impact (Arvizo et al., 2010; Chandra et al., 2013).

Through this paper, we endeavour to provide insights into the remarkable properties and applications of gold nanoparticles, paving the way for continued advancements in nanoscience and nanotechnology. By fostering interdisciplinary collaboration and responsible research practices, we can unlock new frontiers and realize the full potential of AuNPs in addressing pressing societal challenges and driving innovation forward.

2. Synthesis and Characterization

The paper provides an analysis of various methods for synthesizing gold nanoparticles, ranging from traditional chemical reduction approaches to more advanced techniques such as green synthesis and template-assisted methods. Special emphasis is given to the importance of characterization techniques, including transmission electron microscopy (TEM), UV-Vis spectroscopy, and dynamic light scattering (DLS), in understanding and optimizing the properties of these nanoparticles.

Synthesis of gold nanoparticles (AuNPs) involves a variety of methods, each offering unique advantages in terms of control over particle size, shape, and surface chemistry. Traditional chemical reduction methods, such as the Turkevich method (Kimling et al., 2006; Turkevich et al., 1951), involve the reduction of gold salts by strong reducing agents, leading to the formation of spherical nanoparticles. However, the size distribution and shape uniformity in these methods can be limited. Other approaches, such as the Brust-Schiffrin method (Brust et al., 1994), utilize phase-transfer reactions to produce monodisperse nanoparticles with controlled sizes.

Green synthesis methods have gained prominence due to their eco-friendly nature and ability to produce nanoparticles under mild reaction conditions. Plant extracts, microorganisms, and biomolecules serve as reducing and stabilizing agents in these approaches. For example, the use of plant extracts, such as Aloe vera (Chandran et al., 2006) or Neem (Azadirachta indica) leaf extract (Shankar et al., 2004), has been demonstrated for the synthesis of AuNPs with tunable properties.

Template-assisted methods offer precise control over the size and shape of nanoparticles by using templates or scaffolds as guides during synthesis. Techniques like the electrochemical deposition method utilize porous templates to fabricate AuNPs with tailored architectures, including nanorods, nanowires, and nanocages (Harish et al., 2023; Pérez-Page et al., 2016; Xue & Tan, 2014).

Characterization of AuNPs is essential for understanding their properties and optimizing their performance in various applications. Transmission electron microscopy (TEM) is widely used to visualize the morphology and size distribution of nanoparticles with high resolution. UV-Vis spectroscopy provides information about the optical properties of AuNPs, including surface plasmon resonance (SPR) characteristics. Dynamic light scattering (DLS) enables the measurement of nanoparticle size distribution in solution, while techniques like X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) offer insights into the crystallinity and surface chemistry of AuNPs (Dreaden, Alkilany, et al., 2012).

3. Applications in Medicine

One of the most exciting areas of gold nanoparticle research is their application in medicine. Gold nanoparticles (AuNPs) hold tremendous potential for revolutionizing various aspects of medicine, including drug delivery, imaging, diagnostics, and therapy. Their unique physicochemical properties, biocompatibility, and surface functionalization capabilities make them particularly well-suited for biomedical applications. The paper explores their use in drug delivery, imaging, and diagnostics, highlighting the unique ability of AuNPs to target specific cells and tissues. The potential for synergistic therapeutic effects, such as photothermal and photodynamic therapy, is also discussed.

3.1. Drug Delivery

Gold nanoparticles (AuNPs) have garnered significant attention as promising carriers for drug delivery due to their unique physicochemical properties, which can be tailored to enhance therapeutic efficacy and minimize side effects. The functionalization of AuNPs with targeting ligands and therapeutic agents allows for precise delivery to specific cells or tissues, improving the therapeutic index of drugs. Several studies have demonstrated the potential of AuNPs in various drug delivery applications (Ghobashy et al., 2024; Kong et al., 2017). AuNPs serve as effective carriers for delivering therapeutic agents to specific targets within the body. Functionalization of AuNPs with targeting ligands, such as antibodies or peptides, enables precise delivery to diseased cells or tissues. Additionally, AuNPs can encapsulate drugs within their core or be loaded onto their surface, protecting the payload from degradation and enhancing its bioavailability. This targeted drug delivery approach minimizes off-target effects and improves therapeutic outcomes (Dreaden, Alkilany, et al., 2012; Fratoddi et al., 2014; Kong et al., 2017; Mieszawska et al., 2013; Siddique & Chow, 2020).

3.1.1. Targeted Drug Delivery

AuNPs can be functionalized with targeting ligands, such as antibodies, peptides, or aptamers, that recognize specific receptors overexpressed on the surface of diseased cells, such as cancer cells. By conjugating these targeting moieties to the surface of AuNPs, drugs can be delivered selectively to the target cells, minimizing systemic toxicity and maximizing therapeutic efficacy (Dreaden, Alkilany, et al., 2012). For example, AuNPs functionalized with anti-HER2 antibodies have been used for targeted delivery of chemotherapeutic drugs to HER2-positive breast cancer cells (Khorshid et al., 2023; Sitia et al., 2022; White et al., 2020).

3.1.2. Enhanced Drug Stability and Bioavailability

AuNPs can encapsulate drugs within their core or adsorb them onto their surface, protecting the payload from degradation and improving its bioavailability. This encapsulation or loading process can enhance the stability of drugs, prolong their circulation time in the body, and facilitate their uptake by target cells (Dreaden, Austin, et al., 2012; W. Li et al., 2019). For instance, AuNPs loaded with anticancer drugs, such as doxorubicin or paclitaxel, have shown improved therapeutic efficacy compared to free drugs in preclinical studies (He et al., 2021; C.-S. Lee et al., 2020; Paciotti et al., 2006).

3.1.3. Controlled Release

The unique properties of AuNPs enable controlled release of drugs at the target site through stimuli-responsive mechanisms. AuNPs can be engineered to respond to external stimuli, such as light, temperature, or pH, triggering the release of encapsulated drugs in a controlled manner (Tian et al., 2016; Yetisgin et al., 2020). This spatiotemporal control over drug release can minimize off-target effects and enhance therapeutic outcomes.

3.1.4. Combination Therapy

AuNPs offer the opportunity for combination therapy by co-delivering multiple therapeutic agents, such as drugs, nucleic acids, or imaging agents, within the same nanoparticle platform. This approach allows for synergistic therapeutic effects, where different agents act in concert to enhance efficacy and overcome drug resistance (Beik et al., 2019; He et al., 2021). For example, AuNPs have been used for co-delivery of chemotherapeutic drugs and siRNA to cancer cells, leading to improved therapeutic outcomes (H. Huang et al., 2023).

Overall, AuNPs hold great promise as versatile carriers for drug delivery, offering opportunities to improve the efficacy, safety, and targeted delivery of therapeutic agents in various disease settings.

3.2. Imaging

Gold nanoparticles (AuNPs) exhibit unique optical properties, including surface plasmon resonance (SPR), that make them valuable contrast agents for various imaging modalities in medicine. These imaging techniques leverage the strong interaction between AuNPs and electromagnetic radiation, enabling sensitive detection and visualization of biological structures. AuNPs can enhance the contrast in techniques such as computed tomography (CT), photoacoustic imaging, and surface-enhanced Raman scattering (SERS) imaging (Si et al., 2021; Wu et al., 2019). Functionalized AuNPs can selectively accumulate in tumor tissues, enabling the visualization of tumors with high sensitivity and specificity (Dreaden, Austin, et al., 2012; Dreaden & El-Sayed, 2012).

3.2.1. Computed Tomography (CT)

AuNPs serve as effective contrast agents for CT imaging due to their high X-ray attenuation coefficient, which results in strong contrast enhancement in CT scans. The high atomic number of gold enables efficient absorption of X-rays, leading to enhanced image contrast and improved resolution (Hainfeld et al., 2004; Jiang et al., 2023). AuNPs can accumulate selectively in target tissues, such as tumors, enabling precise visualization of pathological features with high sensitivity (Dreaden, Austin, et al., 2012; Dreaden & El-Sayed, 2012). Furthermore, AuNPs can be functionalized with targeting ligands to enhance specificity and enable molecular imaging (Q.-Y. Cai et al., 2007; Nejati et al., 2022).

3.2.2. Photoacoustic Imaging

Photoacoustic imaging combines the high spatial resolution of ultrasound with the high contrast of optical imaging, offering deep tissue imaging capabilities. AuNPs exhibit strong absorption of near-infrared (NIR) light, leading to localized heating and generation of acoustic waves through the photoacoustic effect. This allows for sensitive detection of AuNP-labeled tissues with high resolution and depth penetration (Y. Wang et al., 2004).

3.2.3. Surface-Enhanced Raman Scattering (SERS) Imaging

SERS imaging exploits the surface plasmon resonance (SPR) properties of AuNPs to enhance the Raman scattering signal of nearby molecules. AuNPs can amplify the Raman signals of molecules adsorbed on their surface by several orders of magnitude, enabling sensitive detection and imaging of biomolecules. This technique offers molecular specificity and multiplexing capabilities, allowing for simultaneous detection of multiple targets in complex biological samples (Kneipp et al., 1999; Wu et al., 2019).

The integration of AuNPs into imaging modalities holds great promise for advancing diagnostic capabilities in medicine, enabling early detection, accurate diagnosis, and precise localization of diseases. Moreover, AuNP-based imaging agents can be engineered to target specific biological processes or molecular markers, facilitating personalized and targeted treatment strategies.

3.3. Diagnostics

Gold nanoparticles (AuNPs) have emerged as versatile tools for diagnostic applications, offering sensitive and specific detection of biomolecules and disease markers. Functionalized AuNPs are used as probes in techniques like lateral flow assays, colorimetric assays, and surface plasmon resonance (SPR)-based biosensors. These assays offer rapid, sensitive, and cost-effective detection of biomarkers for diseases such as cancer, infectious diseases, and cardiovascular disorders (Chandra et al., 2013; Daraee et al., 2016; Singh et al., 2018).

3.3.1. Lateral Flow Assays

Lateral flow assays (LFAs) are simple and rapid diagnostic tests that utilize the flow of fluids along a membrane to detect the presence of a target analyte. AuNPs are commonly used as labels in LFAs due to their unique optical properties, which enable visual detection of the assay result. In LFAs, AuNPs functionalized with specific recognition molecules, such as antibodies or DNA probes, bind to the target analyte, resulting in a visible colour change that indicates the presence or absence of the target. LFAs have been widely used for the rapid detection of various analytes, including infectious pathogens, biomarkers, and environmental contaminants (Posthuma-Trumpie et al., 2009).

3.3.2. Colorimetric Assays

Colorimetric assays based on the aggregation or dispersion of AuNPs offer a simple and sensitive platform for detecting analytes of interest. In these assays, the optical properties of AuNPs change in response to the presence of the target analyte, leading to a visible colour change that can be detected with the naked eye or measured spectrophotometrically. AuNP-based colorimetric assays have been developed for the detection of nucleic acids, proteins, small molecules, and ions. These assays offer rapid and sensitive detection without the need for specialized equipment, making them suitable for point-of-care testing and resource-limited settings (Elghanian et al., 1997; Xie et al., 2012).

3.3.3. Surface Plasmon Resonance (SPR) Biosensors

AuNPs are also used as sensing elements in surface plasmon resonance (SPR) biosensors for label-free detection of biomolecular interactions. SPR biosensors rely on the changes in the refractive index of the surrounding medium upon binding of target molecules to immobilized ligands on the sensor surface. AuNPs can enhance the sensitivity of SPR biosensors by amplifying the SPR signal through localized surface plasmon resonance (LSPR) effects. AuNP-based SPR biosensors have been employed for the detection of biomolecules such as proteins, nucleic acids, and small molecules with high sensitivity and specificity (Homola et al., 1999).

3.3.4. Molecular Imaging

AuNPs functionalized with targeting ligands or imaging agents can be used for molecular imaging of biological processes and disease markers. AuNP-based imaging probes enable non-invasive visualization and quantification of specific molecular targets in vivo, providing valuable information for disease diagnosis and treatment monitoring (Jokerst et al., 2012; Jokerst & Gambhir, 2011). Molecular imaging techniques such as positron emission tomography (PET), single-photon emission computed tomography (SPECT), magnetic resonance imaging (MRI), and fluorescence imaging have been combined with AuNP-based probes for various diagnostic applications (X. Li et al., 2016; Padmanabhan et al., 2016).

AuNP-based diagnostic platforms offer several advantages, including high sensitivity, specificity, and multiplexing capability, as well as simplicity and rapidity of assay performance. These platforms have the potential to revolutionize disease diagnosis and management by enabling early detection, accurate diagnosis, and personalized treatment strategies.

3.4. Therapy

Gold nanoparticles (AuNPs) have emerged as promising agents for various therapeutic modalities in medicine, including photothermal therapy (PTT), photodynamic therapy (PDT), chemotherapy, and gene therapy. In PTT, AuNPs selectively accumulate in tumors and convert near-infrared (NIR) light into heat, leading to localized hyperthermia and tumor ablation. In PDT, AuNPs are conjugated with photosensitizers and selectively accumulate in cancer cells, where they generate reactive oxygen species upon irradiation with light, inducing cell death (X. Huang et al., 2006). The unique physicochemical properties of AuNPs, combined with their biocompatibility and tunable surface chemistry, enable their use as versatile platforms for targeted and localized therapeutic interventions.

3.4.1. Photothermal Therapy (PTT)

PTT harnesses the ability of AuNPs to convert absorbed light into heat, leading to localized hyperthermia and selective ablation of target tissues, such as tumors. AuNPs with plasmon resonance peaks in the near-infrared (NIR) region are particularly suited for PTT, as NIR light can penetrate deep into tissues with minimal absorption and scattering. Upon irradiation with NIR light, AuNPs generate heat through non-radiative relaxation processes, causing thermal damage to cancer cells while sparing surrounding healthy tissues. PTT offers the advantages of precise spatial and temporal control over treatment, minimal invasiveness, and reduced systemic toxicity (Hirsch et al., 2003).

3.4.2. Photodynamic Therapy (PDT)

AuNPs can also serve as carriers for photosensitizers in PDT, a minimally invasive therapeutic modality for treating cancer and other diseases. In PDT, photosensitizing agents localized in target tissues are activated by light of specific wavelengths, leading to the generation of reactive oxygen species (ROS) that induce cell death through oxidative damage. AuNPs can enhance the efficacy of PDT by facilitating the delivery and retention of photosensitizers in target tissues, as well as by serving as optical antennas to enhance light absorption and ROS generation. PDT with AuNP-based formulations offers the potential for synergistic therapeutic effects and improved treatment outcomes (Chatterjee et al., 2008; Lucky et al., 2015).

3.4.3. Chemotherapy

AuNPs can be used as carriers for chemotherapeutic drugs, enhancing their delivery to target tissues and reducing systemic toxicity. AuNPs can be functionalized with targeting ligands to selectively accumulate in diseased tissues, such as tumors, where they release encapsulated drugs in response to stimuli such as pH, temperature, or enzymatic activity. This targeted drug delivery approach improves the therapeutic index of chemotherapeutic agents, minimizing off-target effects and enhancing efficacy (Dreaden, Austin, et al., 2012; Dreaden & El-Sayed, 2012).

3.4.4. Gene Therapy

AuNPs have shown promise as non-viral vectors for gene delivery in gene therapy applications. AuNPs can complex with nucleic acids, such as DNA or RNA, and facilitate their intracellular delivery, protecting them from degradation and enhancing transfection efficiency. AuNP-based gene delivery systems offer advantages such as biocompatibility, stability, and tunable surface properties, enabling precise control over gene delivery and expression (Bahadur K.C. et al., 2014; Mendes et al., 2022).

Overall, AuNPs hold great promise for advancing therapeutic interventions in medicine, offering innovative approaches for targeted and personalized treatments across a wide range of diseases. Further research and development efforts are needed to optimize AuNP-based therapeutic strategies and translate them into clinical applications. The transformative potential of gold nanoparticles in medicine is evident in numerous preclinical and clinical studies, highlighting their versatility and efficacy across a range of applications. However, challenges such as biocompatibility, pharmacokinetics, and long-term safety need to be addressed for their successful translation into clinical practice.

4. Electronics and Catalysis

Gold nanoparticles (AuNPs) have garnered significant interest in the fields of electronics and catalysis due to their unique electronic, optical, and catalytic properties. The exceptional conductivity, stability, and tunability of AuNPs make them valuable components in electronic devices, while their catalytic activity and selectivity enable them to facilitate various chemical reactions with high efficiency. The paper investigates their role in enhancing the performance of electronic devices and catalyzing chemical reactions with high efficiency. Applications in sensors and renewable energy are also explored, showcasing the multifaceted contributions of gold nanoparticles in these fields.

4.1. Electronics

AuNPs are widely used in electronics for their excellent electrical conductivity and stability. Their exceptional conductivity, stability, and tunability make them valuable components in various electronic devices, ranging from sensors and transistors to memory devices and display technologies. They serve as key components in nanoelectronic devices such as field-effect transistors (FETs), sensors, and memory devices. AuNPs can be incorporated into electronic circuits to enhance conductivity, improve device performance, and enable miniaturization. Furthermore, the ability to functionalize AuNPs with organic molecules or biomolecules enables their integration into bioelectronic devices for sensing and interfacing with biological systems (Homberger & Simon, 2010; Yassin, 2023).

4.1.1. Field-Effect Transistors (FETs)

AuNPs are widely utilized in the fabrication of FETs due to their excellent electrical conductivity and stability. By incorporating AuNPs as electrodes or channel materials, researchers have developed FETs with enhanced performance, including high charge carrier mobility, low operating voltages, and improved on/off ratios. These AuNP-based FETs find applications in flexible and wearable electronics, as well as in biosensing platforms (B. Cai et al., 2015; De Moraes & Kubota, 2016; Dong et al., 2008; Presnova et al., 2017).

4.1.2. Sensors

AuNPs are extensively employed in sensor technologies for their ability to transduce chemical and biological signals into measurable electrical signals. Functionalized AuNPs can serve as sensing elements in various types of sensors, including optical, electrochemical, and surface plasmon resonance (SPR) sensors. AuNP-based sensors offer advantages such as high sensitivity, rapid response times, and low detection limits, making them suitable for applications in environmental monitoring, healthcare diagnostics, and food safety (Chinchulkar et al., 2023; Elghanian et al., 1997; Sadiq et al., 2023).

4.1.3. Memory Devices

AuNPs are explored for their potential application in non-volatile memory devices due to their unique charge storage properties. AuNPs embedded in a dielectric matrix can trap and release charge carriers, enabling data storage in memory devices. Researchers have demonstrated AuNP-based memory devices with promising characteristics, including high storage density, fast switching speeds, and low power consumption. These devices hold potential for future developments in data storage technologies (Ahmad et al., 2012; Cui et al., 2011; J.-S. Lee, 2010).

4.1.4. Bioelectronics

AuNPs are increasingly utilized in bioelectronic devices for interfacing with biological systems and monitoring physiological signals. Functionalized AuNPs can facilitate the immobilization of biomolecules, such as enzymes, antibodies, or nucleic acids, enabling the development of biosensors, biofuel cells, and implantable medical devices. AuNP-based bioelectronics offer opportunities for sensitive and selective detection of biomarkers, as well as for therapeutic interventions in healthcare applications (Kader et al., 2023; Siciliano et al., 2024).

The integration of AuNPs into electronic devices has led to significant advancements in various fields, including information technology, healthcare, and environmental monitoring. Further research efforts are focused on exploring novel fabrication techniques, understanding fundamental electronic properties, and optimizing AuNP-based materials for enhanced performance and functionality in electronic applications

4.2. Catalysis

AuNPs exhibit remarkable catalytic activity and selectivity in various chemical reactions, making them valuable catalysts for organic synthesis, environmental remediation, and energy conversion processes. The unique properties of AuNPs, such as their high surface area-to-volume ratio and tunable surface chemistry, and strong interaction with reactant molecules, enable precise control over catalytic reactions and facilitate the design of efficient catalysts. AuNPs can catalyze a wide range of reactions, including oxidation, reduction, hydrogenation, and carbon-carbon bond formation, under mild reaction conditions. Additionally, the size, shape, and composition of AuNPs can be tailored to optimize catalytic performance and selectivity for specific reactions. (Chakroborty et al., 2024; Corma & Garcia, 2008; Wani et al., 2021).

4.2.1. Organic Synthesis

AuNPs catalyze a diverse array of organic transformations, including oxidation, reduction, hydrogenation, and carbon-carbon bond formation reactions. One of the most well-known examples is the use of AuNPs as catalysts in the aerobic oxidation of alcohols to aldehydes and ketones. AuNPs exhibit high catalytic activity under mild reaction conditions, such as room temperature and atmospheric pressure, making them attractive catalysts for sustainable and environmentally benign synthesis routes (Corma & Garcia, 2008). Additionally, AuNPs can catalyze cascade reactions and multi-step transformations, enabling the synthesis of complex organic molecules with high efficiency (Chen et al., 2023; Deshmukh et al., 2021).

4.2.2. Environmental Remediation

AuNPs have been explored for their potential applications in environmental catalysis, particularly in the degradation of organic pollutants and the removal of toxic contaminants from air and water. AuNPs can catalyze the oxidation of organic pollutants, such as volatile organic compounds (VOCs) and aromatic hydrocarbons, through processes such as catalytic combustion and photocatalysis. AuNP-based catalysts offer advantages such as high catalytic activity, selectivity, and stability, as well as the possibility of recycling and reusing the catalysts for multiple cycles (Hashmi, 2010; Hashmi et al., 2007; Hashmi & Hutchings, 2006).

4.2.3. Energy Conversion

AuNPs play a crucial role in energy conversion processes, including the conversion of solar energy into chemical fuels and the production of hydrogen through water splitting reactions. Additionally, AuNPs can catalyze the electrochemical and photochemical splitting of water to generate hydrogen gas, a clean and sustainable fuel for various applications (W. Li et al., 2019; Sarfraz & Khan, 2021). AuNPs can catalyze the reduction of carbon dioxide (CO_2) to produce value-added chemicals and fuels, such as methane, methanol, and formic acid, using renewable energy sources (Alli et al., 2023; Olajire, 2018). AuNP-based catalysts offer opportunities for developing efficient and cost-effective technologies for renewable energy conversion and storage (Gurunathan et al., 2014).

The integration of AuNPs into electronic and catalytic systems has led to significant advancements in various applications, including sensing, energy storage, pharmaceuticals, materials science, environmental engineering, and chemical synthesis. Further research efforts are focused on exploring novel synthetic strategies, understanding catalytic mechanisms, optimizing catalyst design, and scaling up AuNP-based catalytic processes for industrial applications.

5. Challenges and Future Perspectives

While the potential of gold nanoparticles is vast, the paper acknowledges current challenges and potential risks associated with their widespread use. Concerns regarding toxicity, scalability, and environmental impact are discussed. Future perspectives on addressing these challenges and expanding the horizons of gold nanoparticle applications are presented, emphasizing the need for interdisciplinary collaboration and continued research.

5.1. Biocompatibility and Toxicity

Despite their widespread use in biomedical applications, concerns regarding the biocompatibility and potential toxicity of AuNPs persist. Further research is needed to thoroughly understand the interactions of AuNPs with biological systems, including their biodistribution, cellular uptake mechanisms, and long-term effects in vivo. Strategies for mitigating potential toxicity, such as surface modification and biodegradation, should be explored to ensure the safe and effective use of AuNPs in clinical settings (Albanese & Chan, 2011; Alkilany & Murphy, 2010).

5.2. Scalability and Reproducibility

The synthesis and functionalization of AuNPs often involve complex and labor-intensive processes, leading to challenges in scalability and reproducibility. Developing robust and scalable synthesis methods for producing AuNPs with precise control over size, shape, and surface properties is essential for large-scale manufacturing and commercialization. Additionally, standardization of experimental protocols and characterization techniques is necessary to ensure reproducibility and comparability of results across different research groups (Fu et al., 2007; Lin et al., 2016; Oliveira et al., 2020).

5.3. Cost-effectiveness and Accessibility

The widespread adoption of AuNP-based technologies in various applications depends on their cost-effectiveness and accessibility. While significant progress has been made in reducing the production costs of AuNPs, further optimization of synthesis methods and raw material utilization is needed to make AuNPs more economically viable for commercial applications. Additionally, efforts to enhance the accessibility of AuNP-based technologies, particularly in resource-limited settings, through technology transfer, capacity building, and collaborative research initiatives, can accelerate their global impact (Akintelu et al., 2021; Bharadwaj et al., 2021).

5.4. Multifunctionality and Integration

AuNPs offer unique opportunities for multifunctional and integrated systems by combining different functionalities within a single nanoparticle platform. Future research directions include the development of AuNP-based systems with enhanced multifunctionality, such as theranostic nanoparticles capable of simultaneous imaging and therapy, as well as smart materials with stimuli-responsive properties for controlled drug release and sensing applications. Integration of AuNPs with other nanomaterials and technologies, such as graphene, quantum dots, and microfluidics, can further expand their capabilities and applications (W. Li et al., 2019; Si et al., 2021; Z. Wang et al., 2020).

5.5. Emerging Trends and Applications

Looking ahead, emerging trends and applications of AuNPs are likely to shape future research directions. These may include advances in precision medicine and personalized therapies enabled by AuNP-based drug delivery systems, innovations in wearable and implantable electronics incorporating AuNP-based sensors and actuators, and developments in sustainable energy technologies leveraging AuNP-based catalysts for renewable energy conversion and storage. Exploring these emerging trends and fostering interdisciplinary collaborations can drive innovation and accelerate the translation of AuNP research into real-world applications (Dreaden, Alkilany, et al., 2012; Mitchell et al., 2021).

Addressing the challenges and embracing the future perspectives of AuNP research requires collaborative efforts from researchers, industry stakeholders, policymakers, and funding agencies. By overcoming technical barriers, promoting interdisciplinary research, and fostering innovation, AuNPs have the potential to revolutionize various fields and address some of the most pressing challenges facing society.

6. Conclusion

Gold nanoparticles (AuNPs) represent a versatile and multifunctional class of nanomaterials with immense potential across diverse fields, including medicine, electronics, catalysis, and environmental remediation. This paper provides a comprehensive exploration of the synthesis, characterization, and applications of gold nanoparticles in various advanced fields. By harnessing their unique properties, researchers can unlock innovative solutions for challenges in medicine, electronics, catalysis, and beyond. The future holds great promise for the continued development and application of gold nanoparticles in diverse scientific and technological endeavours.

In medicine, AuNPs have been extensively explored for diagnostic imaging, drug delivery, and therapy, offering opportunities for early disease detection, targeted treatment, and personalized medicine. Their ability to interact with biological systems at the nanoscale level makes them valuable tools for advancing biomedical research and clinical practice.

In electronics, AuNPs play a crucial role in the development of next-generation electronic devices, sensors, and memory devices. Their exceptional electrical conductivity, stability, and compatibility with biomolecules enable the integration of AuNPs into electronic circuits and bioelectronic systems for sensing, computing, and interfacing with biological systems.

In catalysis, AuNPs exhibit remarkable catalytic activity and selectivity in various chemical reactions, ranging from organic synthesis to environmental remediation and energy conversion processes. Their unique catalytic properties, such as high surface reactivity and tunable surface chemistry, offer opportunities for developing efficient and sustainable catalytic technologies for addressing global challenges in energy, environment, and healthcare.

Despite the significant progress made in AuNP research, several challenges remain to be addressed, including biocompatibility, scalability, cost-effectiveness, and integration of multifunctionality. By overcoming these challenges and embracing emerging trends and applications, AuNPs have the potential to revolutionize various fields and contribute to solving some of the most pressing challenges facing society. Continued research efforts, interdisciplinary collaborations, and technological innovations are essential for unlocking the full capabilities of AuNPs and translating them into real-world solutions.

Acknowledgement

The author is grateful to his Ph.D. guide Prof. Syed Sirajul Islam, former Professor, Department of Chemistry and Chemical Technology, Vidyasagar University, West Bengal, for his continuous encouragement and constructive suggestions. The author is also grateful to his Institute for providing necessary research facilities.

Conflict of interest

The author declares no conflict of interest.

References

Ahmad, Z., Ooi, P. C., Sulaiman, K., Aw, K. C., & Sayyad, M. H. (2012). Programmable nonvolatile memory based on gold nanoparticles in poly-methyl-silsesquioxane sol–gel. *Microelectronic Engineering*, *99*, 62–66. https://doi.org/10.1016/j.mee.2012.07.106

Akintelu, S. A., Yao, B., & Folorunso, A. S. (2021). Bioremediation and pharmacological applications of gold nanoparticles synthesized from plant materials. *Heliyon*, *7*(3), e06591. https://doi.org/10.1016/j.heliyon.2021.e06591

Albanese, A., & Chan, W. C. W. (2011). Effect of Gold Nanoparticle Aggregation on Cell Uptake and Toxicity. *ACS Nano*, *5*(7), 5478–5489. https://doi.org/10.1021/nn2007496

Alkilany, A. M., & Murphy, C. J. (2010). Toxicity and cellular uptake of gold nanoparticles: What we have learned so far? *Journal of Nanoparticle Research*, *12*(7), 2313–2333. https://doi.org/10.1007/s11051-010-9911-8

Alli, Y. A., Oladoye, P. O., Ejeromedoghene, O., Bankole, O. M., Alimi, O. A., Omotola, E. O., Olanrewaju, C. A., Philippot, K., Adeleye, A. S., & Ogunlaja, A. S. (2023). Nanomaterials as catalysts for CO2 transformation into value-added products: A review. *Science of The Total Environment*, *868*, 161547. https://doi.org/10.1016/j.scitotenv.2023.161547

Arvizo, R., Bhattacharya, R., & Mukherjee, P. (2010). Gold nanoparticles: Opportunities and challenges in nanomedicine. *Expert Opinion on Drug Delivery*, *7*(6), 753–763. https://doi.org/10.1517/17425241003777010

Bahadur K.C., R., Thapa, B., & Bhattarai, N. (2014). Gold nanoparticle-based gene delivery: Promises and challenges. *Nanotechnology Reviews*, *3*(3). https://doi.org/10.1515/ntrev-2013-0026

Beik, J., Khateri, M., Khosravi, Z., Kamrava, S. K., Kooranifar, S., Ghaznavi, H., & Shakeri-Zadeh, A. (2019). Gold nanoparticles in combinatorial cancer therapy strategies. *Coordination Chemistry Reviews*, *387*, 299–324. https://doi.org/10.1016/j.ccr.2019.02.025

Bharadwaj, K. K., Rabha, B., Pati, S., Sarkar, T., Choudhury, B. K., Barman, A., Bhattacharjya, D., Srivastava, A., Baishya, D., Edinur, H. A., Abdul Kari, Z., & Mohd Noor, N. H. (2021). Green Synthesis of Gold Nanoparticles Using Plant Extracts as Beneficial Prospect for Cancer Theranostics. *Molecules*, *26*(21), 6389. https://doi.org/10.3390/molecules26216389

Boisselier, E., & Astruc, D. (2009). Gold nanoparticles in nanomedicine: Preparations, imaging, diagnostics, therapies and toxicity. *Chemical Society Reviews*, *38*(6), 1759. https://doi.org/10.1039/b806051g

Brust, M., Walker, M., Bethell, D., Schiffrin, D. J., & Whyman, R. (1994). Synthesis of thiol-derivatised gold nanoparticles in a two-phase Liquid–Liquid system. *J. Chem. Soc., Chem. Commun.*, *0*(7), 801–802. https://doi.org/10.1039/C39940000801

Cai, B., Huang, L., Zhang, H., Sun, Z., Zhang, Z., & Zhang, G.-J. (2015). Gold nanoparticles-decorated graphene field-effect transistor biosensor for femtomolar MicroRNA detection. *Biosensors and Bioelectronics*, *74*, 329–334. https://doi.org/10.1016/j.bios.2015.06.068

Cai, Q.-Y., Kim, S. H., Choi, K. S., Kim, S. Y., Byun, S. J., Kim, K. W., Park, S. H., Juhng, S. K., & Yoon, K.-H. (2007). Colloidal Gold Nanoparticles as a Blood-Pool Contrast Agent for X-ray Computed Tomography in Mice: *Investigative Radiology*, *42*(12), 797–806. https://doi.org/10.1097/RLI.0b013e31811ecdcd

Chakroborty, S., Malviya, J., Mishra, D. R., Mishra, N. P., Panda, B. S., Panda, A. R., Mohapatra, S. S., Yadav, S., & Gupta, D. (2024). A Detailed Investigation and Catalytic Application of Gold Nanoparticles Towards Synthesis of N & O-Heterocycles. *Topics in Catalysis*, *67*(1–4), 123–139. https://doi.org/10.1007/s11244-023-01884-7

Chandra, P., Singh, J., Singh, A., Srivastava, A., Goyal, R. N., & Shim, Y. B. (2013). Gold Nanoparticles and Nanocomposites in Clinical Diagnostics Using Electrochemical Methods. *Journal of Nanoparticles*, *2013*, 1–12. https://doi.org/10.1155/2013/535901

Chandran, S. P., Chaudhary, M., Pasricha, R., Ahmad, A., & Sastry, M. (2006). Synthesis of Gold Nanotriangles and Silver Nanoparticles Using Aloe vera Plant Extract. *Biotechnology Progress*, *22*(2), 577–583. https://doi.org/10.1021/bp0501423

Chatterjee, D. K., Fong, L. S., & Zhang, Y. (2008). Nanoparticles in photodynamic therapy: An emerging paradigm. *Advanced Drug Delivery Reviews*, *60*(15), 1627–1637. https://doi.org/10.1016/j.addr.2008.08.003

Chen, H., Wang, F., & Xue, S. (2023). Novel biosynthetic AuNPs as the efficient catalyst for organic contaminants degradation: One-step preparation, degradation kinetics and mechanism. *Research on Chemical Intermediates*, *49*(7), 3045–3063. https://doi.org/10.1007/s11164-023-05026-2

Chinchulkar, S. A., Patra, P., Dehariya, D., Appidi, T., & Rengan, A. K. (2023). Gold nanoparticle–based biosensing applications and fundamentals of sensor technology: Principles and novel designs. In *Fundamentals of Sensor Technology* (pp. 669–723). Elsevier. https://doi.org/10.1016/B978-0-323-88431-0.00014-4

Corma, A., & Garcia, H. (2008). Supported gold nanoparticles as catalysts for organic reactions. *Chemical Society Reviews*, *37*(9), 2096. https://doi.org/10.1039/b707314n

Cui, P., Seo, S., Lee, J., Wang, L., Lee, E., Min, M., & Lee, H. (2011). Nonvolatile Memory Device Using Gold Nanoparticles Covalently Bound to Reduced Graphene Oxide. *ACS Nano*, *5*(9), 6826–6833. https://doi.org/10.1021/nn2021875

Daraee, H., Eatemadi, A., Abbasi, E., Fekri Aval, S., Kouhi, M., & Akbarzadeh, A. (2016). Application of gold nanoparticles in biomedical and drug delivery. *Artificial Cells, Nanomedicine, and Biotechnology*, *44*(1), 410–422. https://doi.org/10.3109/21691401.2014.955107

De Moraes, A., & Kubota, L. (2016). Recent Trends in Field-Effect Transistors-Based Immunosensors. *Chemosensors*, *4*(4), 20. https://doi.org/10.3390/chemosensors4040020

Deshmukh, A. R., Aloui, H., & Kim, B. S. (2021). Novel biogenic gold nanoparticles catalyzing multienzyme cascade reaction: Glucose oxidase and peroxidase mimicking activity. *Chemical Engineering Journal*, *421*, 127859. https://doi.org/10.1016/j.cej.2020.127859

Díez, A. G., Rincón-Iglesias, M., Lanceros-Méndez, S., Reguera, J., & Lizundia, E. (2022). Multicomponent magnetic nanoparticle engineering: The role of structure-property relationship in advanced applications. *Materials Today Chemistry*, *26*, 101220. https://doi.org/10.1016/j.mtchem.2022.101220

Dong, X., Lau, C. M., Lohani, A., Mhaisalkar, S. G., Kasim, J., Shen, Z., Ho, X., Rogers, J. A., & Li, L. (2008). Electrical Detection of Femtomolar DNA via Gold-Nanoparticle Enhancement in Carbon-Nanotube-Network Field-Effect Transistors. *Advanced Materials*, *20*(12), 2389–2393. https://doi.org/10.1002/adma.200702798

Dreaden, E. C., Alkilany, A. M., Huang, X., Murphy, C. J., & El-Sayed, M. A. (2012). The golden age: Gold nanoparticles for biomedicine. *Chem. Soc. Rev.*, *41*(7), 2740–2779. https://doi.org/10.1039/C1CS15237H

Dreaden, E. C., Austin, L. A., Mackey, M. A., & El-Sayed, M. A. (2012). Size matters: Gold nanoparticles in targeted cancer drug delivery. *Therapeutic Delivery*, *3*(4), 457–478. https://doi.org/10.4155/tde.12.21

Dreaden, E. C., & El-Sayed, M. A. (2012). Detecting and Destroying Cancer Cells in More than One Way with Noble Metals and Different Confinement Properties on the Nanoscale. *Accounts of Chemical Research*, *45*(11), 1854–1865. https://doi.org/10.1021/ar2003122

Dykman, L. A., & Khlebtsov, N. G. (2011). Gold nanoparticles in biology and medicine: Recent advances and prospects. *Acta Naturae*, *3*(2), 34–55.

Elghanian, R., Storhoff, J. J., Mucic, R. C., Letsinger, R. L., & Mirkin, C. A. (1997). Selective Colorimetric Detection of Polynucleotides Based on the Distance-Dependent Optical Properties of Gold Nanoparticles. *Science*, *277*(5329), 1078–1081. https://doi.org/10.1126/science.277.5329.1078

Fratoddi, I., Venditti, I., Cametti, C., & Russo, M. V. (2014). Gold nanoparticles and gold nanoparticle-conjugates for delivery of therapeutic molecules. Progress and challenges. *J. Mater. Chem. B*, *2*(27), 4204–4220. https://doi.org/10.1039/C4TB00383G

Fu, Y., Du, Y., Yang, P., Li, J., & Jiang, L. (2007). Shape-controlled synthesis of highly monodisperse and small size gold nanoparticles. *Science in China Series B: Chemistry*, *50*(4), 494–500. https://doi.org/10.1007/s11426-007-0085-x

Ghobashy, M. M., Alkhursani, Sh. A., Alqahtani, H. A., El-damhougy, T. K., & Madani, M. (2024). Gold nanoparticles in microelectronics advancements and biomedical applications. *Materials Science and Engineering: B*, *301*, 117191. https://doi.org/10.1016/j.mseb.2024.117191

Gurunathan, S., Han, J., Park, J. H., & Kim, J.-H. (2014). A green chemistry approach for synthesizing biocompatible gold nanoparticles. *Nanoscale Research Letters*, *9*(1), 248. https://doi.org/10.1186/1556-276X-9-248

Hainfeld, J. F., Slatkin, D. N., & Smilowitz, H. M. (2004). The use of gold nanoparticles to enhance radiotherapy in mice. *Physics in Medicine and Biology*, *49*(18), N309–N315. https://doi.org/10.1088/0031-9155/49/18/N03

Harish, V., Ansari, M. M., Tewari, D., Yadav, A. B., Sharma, N., Bawarig, S., García-Betancourt, M.-L., Karatutlu, A., Bechelany, M., & Barhoum, A. (2023). Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *Journal of the Taiwan Institute of Chemical Engineers*, *149*, 105010. https://doi.org/10.1016/j.jtice.2023.105010

Hashmi, A. S. K. (2010). Homogeneous Gold Catalysis Beyond Assumptions and Proposals—Characterized Intermediates. *Angewandte Chemie International Edition*, *49*(31), 5232–5241. https://doi.org/10.1002/anie.200907078

Hashmi, A. S. K., & Hutchings, G. J. (2006). Gold Catalysis. *Angewandte Chemie International Edition*, *45*(47), 7896–7936. https://doi.org/10.1002/anie.200602454

Hashmi, A. S. K., Salathé, R., & Frey, W. (2007). Gold Catalysis: Selectivity Problems in Hydroarylations with Pyrroles. *European Journal of Organic Chemistry*, *2007*(10), 1648–1652. https://doi.org/10.1002/ejoc.200601062

He, J., Liu, S., Zhang, Y., Chu, X., Lin, Z., Zhao, Z., Qiu, S., Guo, Y., Ding, H., Pan, Y., & Pan, J. (2021). The Application of and Strategy for Gold Nanoparticles in Cancer Immunotherapy. *Frontiers in Pharmacology*, *12*, 687399. https://doi.org/10.3389/fphar.2021.687399

Hirsch, L. R., Stafford, R. J., Bankson, J. A., Sershen, S. R., Rivera, B., Price, R. E., Hazle, J. D., Halas, N. J., & West, J. L. (2003). Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance. *Proceedings of the National Academy of Sciences*, *100*(23), 13549–13554. https://doi.org/10.1073/pnas.2232479100

Homberger, M., & Simon, U. (2010). On the application potential of gold nanoparticles in nanoelectronics and biomedicine. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *368*(1915), 1405–1453. https://doi.org/10.1098/rsta.2009.0275

Homola, J., Yee, S. S., & Gauglitz, G. (1999). Surface plasmon resonance sensors: Review. *Sensors and Actuators B: Chemical*, *54*(1–2), 3–15. https://doi.org/10.1016/S0925-4005(98)00321-9

Hu, X., Zhang, Y., Ding, T., Liu, J., & Zhao, H. (2020). Multifunctional Gold Nanoparticles: A Novel Nanomaterial for Various Medical Applications and Biological Activities. *Frontiers in Bioengineering and Biotechnology*, *8*, 990. https://doi.org/10.3389/fbioe.2020.00990

Huang, H., Liu, R., Yang, J., Dai, J., Fan, S., Pi, J., Wei, Y., & Guo, X. (2023). Gold Nanoparticles: Construction for Drug Delivery and Application in Cancer Immunotherapy. *Pharmaceutics*, *15*(7), 1868. https://doi.org/10.3390/pharmaceutics15071868

Huang, X., El-Sayed, I. H., Qian, W., & El-Sayed, M. A. (2006). Cancer Cell Imaging and Photothermal Therapy in the Near-Infrared Region by Using Gold Nanorods. *Journal of the American Chemical Society*, *128*(6), 2115–2120. https://doi.org/10.1021/ja057254a

Jiang, Z., Zhang, M., Li, P., Wang, Y., & Fu, Q. (2023). Nanomaterial-based CT contrast agents and their applications in image-guided therapy. *Theranostics*, *13*(2), 483–509. https://doi.org/10.7150/thno.79625

Jokerst, J. V., & Gambhir, S. S. (2011). Molecular imaging with theranostic nanoparticles. *Accounts of Chemical Research*, *44*(10), 1050–1060. https://doi.org/10.1021/ar200106e

Jokerst, J. V., Thangaraj, M., Kempen, P. J., Sinclair, R., & Gambhir, S. S. (2012). Photoacoustic Imaging of Mesenchymal Stem Cells in Living Mice *via* Silica-Coated Gold Nanorods. *ACS Nano*, *6*(7), 5920–5930. https://doi.org/10.1021/nn302042y

Kader, Md. A., Suhaity Azmi, N., & Kafi, A. K. M. (2023). Recent advances in gold nanoparticles modified electrodes in electrochemical nonenzymatic sensing of chemical and biological compounds. *Inorganic Chemistry Communications*, *153*, 110767. https://doi.org/10.1016/j.inoche.2023.110767

Khorshid, M., Varshosaz, J., Rostami, M., Haghiralsadat, F., Akbari, V., & Khorshid, P. (2023). Anti HER-2 aptamer functionalized gold nanoparticles of dasatinib for targeted chemo-radiotherapy in breast cancer cells. *Biomaterials Advances*, *154*, 213591. https://doi.org/10.1016/j.bioadv.2023.213591

Kimling, J., Maier, M., Okenve, B., Kotaidis, V., Ballot, H., & Plech, A. (2006). Turkevich Method for Gold Nanoparticle Synthesis Revisited. *The Journal of Physical Chemistry B*, *110*(32), 15700–15707. https://doi.org/10.1021/jp061667w

Kneipp, K., Kneipp, H., Itzkan, I., Dasari, R. R., & Feld, M. S. (1999). Ultrasensitive Chemical Analysis by Raman Spectroscopy. *Chemical Reviews*, *99*(10), 2957–2976. https://doi.org/10.1021/cr980133r

Kong, F.-Y., Zhang, J.-W., Li, R.-F., Wang, Z.-X., Wang, W.-J., & Wang, W. (2017). Unique Roles of Gold Nanoparticles in Drug Delivery, Targeting and Imaging Applications. *Molecules*, *22*(9), 1445. https://doi.org/10.3390/molecules22091445

Kumar, A., Mazinder Boruah, B., & Liang, X.-J. (2011). Gold Nanoparticles: Promising Nanomaterials for the Diagnosis of Cancer and HIV/AIDS. *Journal of Nanomaterials*, *2011*, 1–17. https://doi.org/10.1155/2011/202187

Lee, C.-S., Kim, T., Oh, D., Bae, S., Ryu, J., Kong, H., Jeon, H., Seo, H., Jeon, S., & Kim, T. (2020). In Vivo and In Vitro Anticancer Activity of Doxorubicin-loaded DNA-AuNP Nanocarrier for the Ovarian Cancer Treatment. *Cancers*, *12*(3), 634. https://doi.org/10.3390/cancers12030634

Lee, J.-S. (2010). Recent progress in gold nanoparticle-based non-volatile memory devices. *Gold Bulletin*, *43*(3), 189–199. https://doi.org/10.1007/BF03214986

Li, W., Cao, Z., Liu, R., Liu, L., Li, H., Li, X., Chen, Y., Lu, C., & Liu, Y. (2019). AuNPs as an important inorganic nanoparticle applied in drug carrier systems. *Artificial Cells, Nanomedicine, and Biotechnology*, *47*(1), 4222–4233. https://doi.org/10.1080/21691401.2019.1687501

Li, X., Zhang, X.-N., Li, X.-D., Chang, J., Li, X., Zhang, X.-N., Li, X.-D., & Chang, J. (2016). Multimodality imaging in nanomedicine and nanotheranostics. *Cancer Biology & Medicine*, *13*(3), 339–348. https://doi.org/10.20892/j.issn.2095-3941.2016.0055

Lin, X., Wu, M., Kuga, S., Endo, T., & Huang, Y. (2016). Synthesis of controllable monodisperse gold nanoparticles using wood material and their catalytic activity for p-nitrophenol reduction. *Polymer Journal*, *48*(8), 919–923. https://doi.org/10.1038/pj.2016.51

Lucky, S. S., Soo, K. C., & Zhang, Y. (2015). Nanoparticles in Photodynamic Therapy. *Chemical Reviews*, *115*(4), 1990–2042. https://doi.org/10.1021/cr5004198

Malik, S., Muhammad, K., & Waheed, Y. (2023). Nanotechnology: A Revolution in Modern Industry. *Molecules*, *28*(2), 661. https://doi.org/10.3390/molecules28020661

Malik, S., Singh, J., Goyat, R., Saharan, Y., Chaudhry, V., Umar, A., Ibrahim, A. A., Akbar, S., Ameen, S., & Baskoutas, S. (2023). Nanomaterials-based biosensor and their applications: A review. *Heliyon*, *9*(9), e19929. https://doi.org/10.1016/j.heliyon.2023.e19929

Mendes, B. B., Conniot, J., Avital, A., Yao, D., Jiang, X., Zhou, X., Sharf-Pauker, N., Xiao, Y., Adir, O., Liang, H., Shi, J., Schroeder, A., & Conde, J. (2022). Nanodelivery of nucleic acids. *Nature Reviews Methods Primers*, *2*(1), 24. https://doi.org/10.1038/s43586-022-00104-y

Mieszawska, A. J., Mulder, W. J. M., Fayad, Z. A., & Cormode, D. P. (2013). Multifunctional Gold Nanoparticles for Diagnosis and Therapy of Disease. *Molecular Pharmaceutics*, *10*(3), 831–847. https://doi.org/10.1021/mp3005885

Milan, J., Niemczyk, K., & Kus-Liśkiewicz, M. (2022). Treasure on the Earth—Gold Nanoparticles and Their Biomedical Applications. *Materials*, *15*(9), 3355. https://doi.org/10.3390/ma15093355

Mitchell, M. J., Billingsley, M. M., Haley, R. M., Wechsler, M. E., Peppas, N. A., & Langer, R. (2021). Engineering precision nanoparticles for drug delivery. *Nature Reviews Drug Discovery*, *20*(2), 101–124. https://doi.org/10.1038/s41573-020-0090-8

Nejati, K., Dadashpour, M., Gharibi, T., Mellatyar, H., & Akbarzadeh, A. (2022). Biomedical Applications of Functionalized Gold Nanoparticles: A Review. *Journal of Cluster Science*, *33*(1), 1–16. https://doi.org/10.1007/s10876-020-01955-9

Olajire, A. A. (2018). Recent progress on the nanoparticles-assisted greenhouse carbon dioxide conversion processes. *Journal of CO2 Utilization*, *24*, 522–547. https://doi.org/10.1016/j.jcou.2018.02.012

Oliveira, J. P., Prado, A. R., Keijok, W. J., Ribeiro, M. R. N., Pontes, M. J., Nogueira, B. V., & Guimarães, M. C. C. (2020). A helpful method for controlled synthesis of monodisperse gold nanoparticles through response surface modeling. *Arabian Journal of Chemistry*, *13*(1), 216–226. https://doi.org/10.1016/j.arabjc.2017.04.003

Paciotti, G. F., Kingston, D. G. I., & Tamarkin, L. (2006). Colloidal gold nanoparticles: A novel nanoparticle platform for developing multifunctional tumor-targeted drug delivery vectors. *Drug Development Research*, *67*(1), 47–54. https://doi.org/10.1002/ddr.20066

Padmanabhan, P., Kumar, A., Kumar, S., Chaudhary, R. K., & Gulyás, B. (2016). Nanoparticles in practice for molecular-imaging applications: An overview. *Acta Biomaterialia*, *41*, 1–16. https://doi.org/10.1016/j.actbio.2016.06.003

Pérez-Page, M., Yu, E., Li, J., Rahman, M., Dryden, D. M., Vidu, R., & Stroeve, P. (2016). Template-based syntheses for shape controlled nanostructures. *Advances in Colloid and Interface Science*, *234*, 51–79. https://doi.org/10.1016/j.cis.2016.04.001

Posthuma-Trumpie, G. A., Korf, J., & Van Amerongen, A. (2009). Lateral flow (immuno)assay: Its strengths, weaknesses, opportunities and threats. A literature survey. *Analytical and Bioanalytical Chemistry*, *393*(2), 569–582. https://doi.org/10.1007/s00216-008-2287-2

Presnova, G., Presnov, D., Krupenin, V., Grigorenko, V., Trifonov, A., Andreeva, I., Ignatenko, O., Egorov, A., & Rubtsova, M. (2017). Biosensor based on a silicon nanowire field-effect transistor functionalized by gold nanoparticles for the highly sensitive determination of prostate specific antigen. *Biosensors and Bioelectronics*, *88*, 283–289. https://doi.org/10.1016/j.bios.2016.08.054

Sadiq, Z., Safiabadi Tali, S. H., Hajimiri, H., Al-Kassawneh, M., & Jahanshahi-Anbuhi, S. (2023). Gold Nanoparticles-Based Colorimetric Assays for Environmental Monitoring and Food Safety Evaluation. *Critical Reviews in Analytical Chemistry*, 1–36. https://doi.org/10.1080/10408347.2022.2162331

Saleh, H. M., & Hassan, A. I. (2023). Synthesis and Characterization of Nanomaterials for Application in Cost-Effective Electrochemical Devices. *Sustainability*, *15*(14), 10891. https://doi.org/10.3390/su151410891

Sarfraz, N., & Khan, I. (2021). Plasmonic Gold Nanoparticles (AuNPs): Properties, Synthesis and their Advanced Energy, Environmental and Biomedical Applications. *Chemistry – An Asian Journal*, *16*(7), 720–742. https://doi.org/10.1002/asia.202001202

Shankar, S. S., Rai, A., Ahmad, A., & Sastry, M. (2004). Rapid synthesis of Au, Ag, and bimetallic Au core–Ag shell nanoparticles using Neem (Azadirachta indica) leaf broth. *Journal of Colloid and Interface Science*, *275*(2), 496–502. https://doi.org/10.1016/j.jcis.2004.03.003

Si, P., Razmi, N., Nur, O., Solanki, S., Pandey, C. M., Gupta, R. K., Malhotra, B. D., Willander, M., & De La Zerda, A. (2021). Gold nanomaterials for optical biosensing and bioimaging. *Nanoscale Advances*, *3*(10), 2679–2698. https://doi.org/10.1039/D0NA00961J

Siciliano, G., Alsadig, A., Chiriacò, M. S., Turco, A., Foscarini, A., Ferrara, F., Gigli, G., & Primiceri, E. (2024). Beyond traditional biosensors: Recent advances in gold nanoparticles modified electrodes for biosensing applications. *Talanta*, *268*, 125280. https://doi.org/10.1016/j.talanta.2023.125280

Siddique, S., & Chow, J. C. L. (2020). Gold Nanoparticles for Drug Delivery and Cancer Therapy. *Applied Sciences*, *10*(11), 3824. https://doi.org/10.3390/app10113824

Sim, S., & Wong, N. (2021). Nanotechnology and its use in imaging and drug delivery (Review). *Biomedical Reports*, *14*(5), 42. https://doi.org/10.3892/br.2021.1418

Singh, P., Pandit, S., Mokkapati, V. R. S. S., Garg, A., Ravikumar, V., & Mijakovic, I. (2018). Gold Nanoparticles in Diagnostics and Therapeutics for Human Cancer. *International Journal of Molecular Sciences*, *19*(7), 1979. https://doi.org/10.3390/ijms19071979

Sitia, L., Sevieri, M., Signati, L., Bonizzi, A., Chesi, A., Mainini, F., Corsi, F., & Mazzucchelli, S. (2022). HER-2-Targeted Nanoparticles for Breast Cancer Diagnosis and Treatment. *Cancers*, *14*(10), 2424. https://doi.org/10.3390/cancers14102424

Tian, L., Lu, L., Qiao, Y., Ravi, S., Salatan, F., & Melancon, M. (2016). Stimuli-Responsive Gold Nanoparticles for Cancer Diagnosis and Therapy. *Journal of Functional Biomaterials*, *7*(3), 19. https://doi.org/10.3390/jfb7030019

Turkevich, J., Stevenson, P. C., & Hillier, J. (1951). A study of the nucleation and growth processes in the synthesis of colloidal gold. *Discussions of the Faraday Society*, *11*, 55. https://doi.org/10.1039/df9511100055

Wang, Y., Xie, X., Wang, X., Ku, G., Gill, K. L., O'Neal, D. P., Stoica, G., & Wang, L. V. (2004). Photoacoustic Tomography of a Nanoshell Contrast Agent in the in Vivo Rat Brain. *Nano Letters*, *4*(9), 1689–1692. https://doi.org/10.1021/nl049126a

Wang, Z., Li, P., Cui, L., Qiu, J.-G., Jiang, B., & Zhang, C. (2020). Integration of nanomaterials with nucleic acid amplification approaches for biosensing. *TrAC Trends in Analytical Chemistry*, *129*, 115959. https://doi.org/10.1016/j.trac.2020.115959

Wani, I. A., Jain, S. K., Khan, H., Kalam, A., & Ahmad, T. (2021). Gold Nanoparticles as Efficient Catalysts in Organic Transformations. *Current Pharmaceutical Biotechnology*, *22*(6), 724–732. https://doi.org/10.2174/1389201022666210218195205

White, B. E., White, M. K., Adhvaryu, H., Makhoul, I., Nima, Z. A., Biris, A. S., & Ali, N. (2020). Nanotechnology approaches to addressing HER2-positive breast cancer. *Cancer Nanotechnology*, *11*(1), 12. https://doi.org/10.1186/s12645-020-00068-2

Wu, Y., Ali, M. R. K., Chen, K., Fang, N., & El-Sayed, M. A. (2019). Gold nanoparticles in biological optical imaging. *Nano Today*, *24*, 120–140. https://doi.org/10.1016/j.nantod.2018.12.006

Xie, X., Xu, W., & Liu, X. (2012). Improving Colorimetric Assays through Protein Enzyme-Assisted Gold Nanoparticle Amplification. *Accounts of Chemical Research*, *45*(9), 1511–1520. https://doi.org/10.1021/ar300044j

Xue, M., & Tan, Y. (2014). Hollow alloy nanostructures templated by Au nanorods: Synthesis, mechanistic insights, and electrocatalytic activity. *Nanoscale*, *6*(21), 12500–12514. https://doi.org/10.1039/C4NR03603D

Yassin, A. Y. (2023). Synthesized polymeric nanocomposites with enhanced optical and electrical properties based on gold nanoparticles for optoelectronic applications. *Journal of Materials Science: Materials in Electronics*, *34*(1), 46. https://doi.org/10.1007/s10854-022-09402-3

Yeh, Y.-C., Creran, B., & Rotello, V. M. (2012). Gold nanoparticles: Preparation, properties, and applications in bionanotechnology. *Nanoscale*, *4*(6), 1871–1880. https://doi.org/10.1039/c1nr11188d

Yetisgin, A. A., Cetinel, S., Zuvin, M., Kosar, A., & Kutlu, O. (2020). Therapeutic Nanoparticles and Their Targeted Delivery Applications. *Molecules*, *25*(9), 2193. https://doi.org/10.3390/molecules25092193