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A Comprehensive Review of Gold Nanoparticles: Properties, Characterization, and Applications

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Abstract

Gold nanoparticles (AuNPs), a versatile family of nanomaterials with a long historical legacy, have been used in stained glass and artwork since ancient times before their recent scientific discovery. Numerous techniques are used to create them, including well-known chemical processes like the Turkevich and Brust-Schiffrin protocols, as well as physical processes like microwave and laser ablation. In order to create more sustainable particles utilizing natural extracts, biological and green synthesis techniques have recently emerged. AuNPs' remarkable utility is directly attributable to their exceptional physicochemical properties, specifically their high surface area, which permits extensive functionalization, and their strong localized surface plasmon resonance (LSPR), which enables them to absorb and scatter light with remarkable efficiency. These characteristics have encouraged their adoption in many different industries. AuNPs are used in gene therapy to deliver nucleic acids to specific cells, in biomedicine for targeted drug administration, and in enhanced biosensing for disease diagnostics. They are also crucial for cosmetics, where their antioxidant properties are utilized to make anti-aging treatments, and agriculture, where they can act as efficient delivery systems for pesticides and fertilizers. With a focus on creating novel hybrid nanomaterials and intelligent, multifunctional nanodevices for a range of applications, AuNPs have a promising future.

Keywords

Gold Nanoparticles (AuNPs), Green Synthesis, Localized Surface Plasmon Resonance (LSPR), Targeted Drug Delivery, Biosensing, Gene Therapy, Hybrid Nanomaterials

1. Introduction

Nanoparticles are materials that have at least one nanoscale dimension, often ranging from 1 to 100 nanometers [1]. Because of their incredibly small size, they have unique physical, chemical, and biological properties that set them apart from their bulk counterparts. This is mostly due to their extraordinarily high surface area to volume ratio, which indicates that a significant amount of their atoms are on the surface and are consequently highly reactive [2]. Due to their unique properties, nanoparticles are now widely used in a wide range of industries and are a key part of nanotechnology [3]. They are used in medicine for targeted drug delivery to treat conditions like cancer, as well as for improved imaging and diagnostics [4]. They are also used in creating electronic components that are quicker, smaller, and more efficient [5].

Nanoparticles are advancing the world of medicine by providing a new method for creating medicinal dosage forms. Nanoparticles are also necessary for improving renewable energy, cleaning up the environment, and developing new materials with better properties, such as self-cleaning surfaces and durable coatings [6]. With several advancements in pharmacy and medicine leading to the creation of novel medications, the field of nanoparticles has a bright future ahead of it [7]. Because of their special size-dependent characteristics, including a high surface area, quantum effects, and surface reactivity, nanoparticles have drawn a lot of attention [8]. These qualities result in improved chemical, mechanical, optical, and electrical capabilities compared to bulk materials. As a result, nanoparticles are employed in many different domains, such as renewable energy technologies, medicine delivery systems, and catalysis [9].

1.1. The Discovery of Gold Nanoparticles

Gold nanoparticles were first observed and described scientifically in the 1850s by renowned physicist and chemist Michael Faraday. He discovered that when gold leaf was dissolved in a solution, it created a ruby-red liquid while he was working on experiments at the Royal Institution (**Figure 1**). He produced the first known pure sample of a gold colloid, making this a significant achievement [10].

Figure 1. Michael Faraday and the First Gold Colloid.

This was a significant discovery since he had produced the first pure sample of a gold colloid. This discovery was revolutionary because it showed that materials might exhibit unique properties both in their bulk and at the nanoscale. Faraday's early research on this "ruby gold" solution created a foundation for the development of nanotechnology. He successfully concluded that the color of the solution was determined by the size of the gold particles that floated in it, which is a fundamental observation of the optical properties of plasmonic nanoparticles [11].

1.2. Modern Applications of Nanotechnology

Nanoparticles and nanotechnology have important applications in many different domains, including biology, physics, chemistry, medicine, and sensing, due to their unique features. The primary characteristics of these particles are their nanoscale size and multifunctionality [12]. They are extensively used in many industrial and medical activities, including targeted therapy, drug and gene delivery, biomedical applications, diagnostics, cosmetics, and environmental fields (**Figure 2**). Improved drug delivery capabilities can also be achieved by combining nanoparticles with medications, imaging markers, and ligands [13].

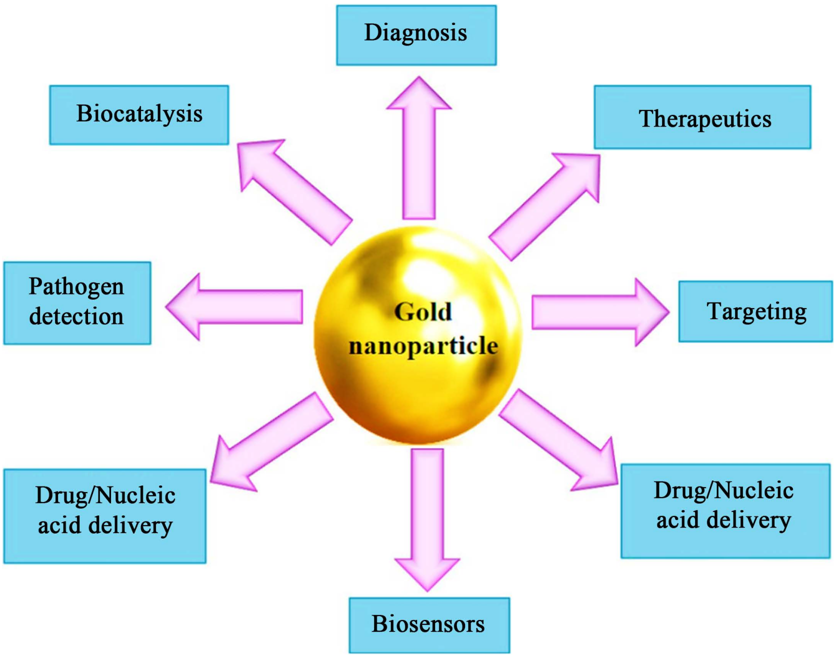

Figure 2. This diagram illustrates the diverse applications of gold nanoparticles across four major fields: medicine, electronics, catalysis, and environmental science. Key uses include drug delivery, biosensors, filtration, and pollutant detection.

2. Gold Nanoparticle Properties

Gold nanoparticles (AuNPs) are extremely desirable due to a number of important properties. The gold-sulfur link gives them great stability, and they are both physiologically and chemically inert [14]. Because of these characteristics, AuNPs can be created to gather in malignant cells and induce cytotoxicity, making them useful as microscopic probes for cancer cell research. Additionally, AuNPs have beneficial electrical characteristics that make them appropriate for a range of analytical techniques and electrode sensors [15].

Localized Surface Plasmon Resonance (LSPR)

Localized Surface Plasmon Resonance (LSPR) is one of the most important optical properties of gold nanoparticles (AuNPs). LSPR refers to the collective oscillation of conduction band electrons that are confined to the surface of individual metallic nanoparticles when they interact with electromagnetic radiation at a specific wavelength [16]. This phenomenon is distinctly different from Surface Plasmon Resonance (SPR), which typically occurs on continuous or planar metal surfaces and involves propagating surface plasmons. In nanoparticles, the plasmon oscillations are spatially confined, leading to strong absorption and scattering of light at characteristic wavelengths. The position and intensity of the LSPR band are highly sensitive to the size, shape, composition, and surrounding dielectric environment of the nanoparticles. According to Mie theory, spherical AuNPs with diameters ranging from approximately 2 to 100 nm exhibit pronounced LSPR effects, which are responsible for the vivid color changes observed in colloidal gold solutions [17]. This localized plasmonic behavior makes AuNPs particularly valuable for applications in biosensing, imaging, and photothermal therapy.

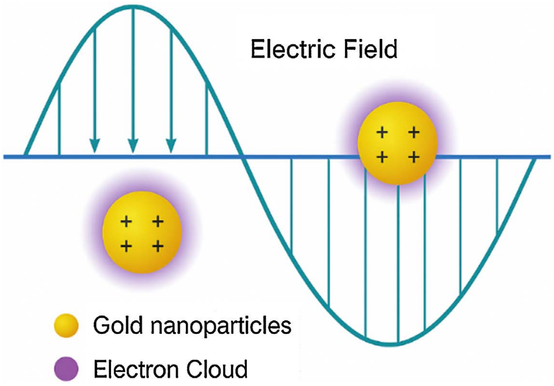

Figure 3. An illustration of localized Surface Plasmon Resonance (LSPR). The electric field of light causes the electron cloud of the gold nanoparticle to oscillate, which is responsible for the particle's distinctive color and optical properties.

3. Classification of Nanoparticles

The composition of nanoparticles allows for their classification into a number of primary kinds. Their distinct qualities and their uses in a variety of domains, such as environmental science, electronics, and medicine, are ascertained through the use of this classification.

The following are the main categories of nanoparticles.

3.1. Inorganic Nanoparticles

There are no carbon-hydrogen bonds in these nanoparticles. They are a broad and varied category that is frequently further divided into groups based on the components that comprise them.

3.1.1. Metal Nanoparticles

Pure metals such as gold, silver, copper, and iron make up metallic nanoparticles, which are prized for their distinct size-dependent characteristics that set them apart from their bulk counterparts. Surface Plasmon Resonance (SPR), a process where light interacts with the free electrons in the nanoparticles to produce high absorption and scattering of particular wavelengths, is one of these particles' unique optical characteristics [18]. Additionally, some metallic nanoparticles, especially silver, have strong antibacterial qualities that make them useful in consumer goods, water purification, and medicinal coatings [19].

3.1.2. Metal Oxide Nanoparticles

A family of nanomaterials known as metal oxide nanoparticles is made up of metal oxides, including iron oxide (Fe_3O_4), zinc oxide (ZnO), and titanium dioxide (TiO_2). Their stability, low toxicity, and distinct physical and chemical characteristics make them extremely valuable [20]. Their large surface area, which increases their reactivity, is a crucial feature. TiO_2 and ZnO nanoparticles are frequently employed in commercial applications, particularly in sunscreens and cosmetics, where they scatter and absorb damaging UV rays to provide superior UV protection [21].

3.1.3. Quantum Dots (QDs) Nanoparticles

Quantum dots (QDs), also referred to as semiconductor nanoparticles, are nanocrystals composed of semiconductor materials like indium phosphide, cadmium selenide, or cadmium telluride. Their ability to emit light of a particular, pure color is their most remarkable characteristic. Because of a phenomenon known as the quantum confinement effect, the size of the nanoparticle determines this hue rather than the substance itself. A quantum dot absorbs energy and re-emits it as light when it is activated by an energy source, such as electrical current or ultraviolet light. It takes more energy to excite the electrons in a smaller quantum dot, which results in shorter wavelengths of light (such as blue). They are perfect for sophisticated applications since the color emitted can be precisely tailored by merely altering the size of the particle. Because of their great brightness and stability, they are most famously employed in QLED TVs to produce vivid, pure colors and in bioimaging as fluorescent probes to observe biological processes and identify particular cells [22].

3.1.4. Ceramic Nanoparticles

A family of nanomaterials known as ceramic nanoparticles is composed of inorganic, non-metallic solids like zirconia (ZrO_2), alumina (Al_2O_3), and silica (SiO_2). They are strong materials that can survive challenging conditions and are well-known for their remarkable chemical and thermal stability. They are especially adaptable due to their large surface area, adjustable porosity, and surface chemistry [23]. For example, because silica nanoparticles may be designed to have a porous structure that enables them to encapsulate and preserve therapeutic molecules until they reach their target, they are frequently utilized in medication delivery. By inhibiting aggregation, ceramic nanoparticles can act as a support for other catalytic materials, extending their lifespan and performance (**Figure 4**).

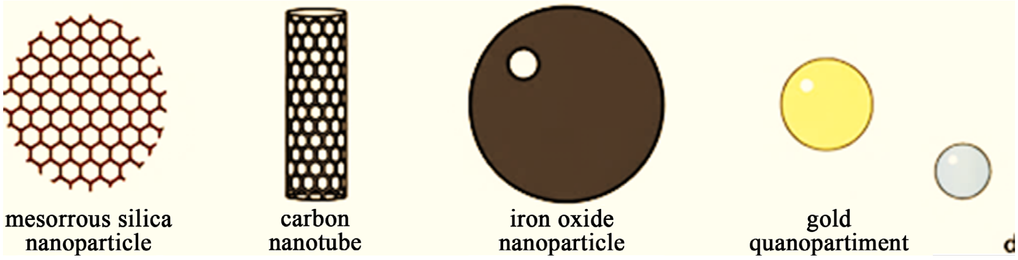

Figure 4. This image displays a comparison of several common inorganic nanoparticles, including mesoporous silica, carbon nanotubes, iron oxide, and gold.

3.2. Organic Nanoparticles

Nanoparticles made of organic compounds fall under this category. They are ideal for biomedical applications since they are frequently biodegradable and biocompatible.

3.2.1. Polymeric Nanoparticles

One kind of nanoparticle made from synthetic or natural polymers is called a polymeric nanoparticle. According to Kamaly *et al.* (2012), these materials can be developed with two main structures: nanospheres, which are solid, homogeneous matrices in which the therapeutic agent is distributed, and nanocapsules, which have a hollow core that contains the medicine and are encased in a thin polymer shell [24]. Because of their structural adaptability, they can act as very efficient carriers for drugs and other therapeutic agents. The capacity of polymeric nanoparticles to provide controlled drug release—that is, to release their payload at a precise rate or in response to a specific trigger, like a change in temperature or pH—is one of their main advantages. Furthermore, their polymer coating acts as a barrier to prevent the body's enzymes from breaking down delicate medicinal substances like proteins and DNA.

3.2.2. Lipid-Based Nanoparticles

A kind of nanoparticles known as "lipid-based nanoparticles" is created from synthetic or natural lipids, which are organic substances such as fats and waxes. Their structure, which enables them to efficiently encapsulate and safeguard medicinal chemicals, is their distinguishing characteristic. The two most prevalent kinds are solid lipid nanoparticles (SLNs), which contain a solid lipid core, and liposomes, which are spherical vesicles with an aqueous core encircled by one or more lipid bilayers [25].

They are perfect for delivering both fat-soluble (in the lipid core of SLNs) and water-soluble (in the aqueous core of liposomes) medications due to their special structure. Important benefits include their biocompatibility and capacity to protect delicate molecules from deterioration within the body. As demonstrated by numerous COVID-19 vaccines, this is especially important for the delivery of genetic elements like messenger RNA (mRNA), where the lipid shell shields the delicate mRNA molecule from being broken down by the body's enzymes before it can enter the cells [26]. This kind, which is composed mostly of carbon atoms, is distinguished by its remarkable conductivity, mechanical strength, and unusual structures (**Figure 5**).

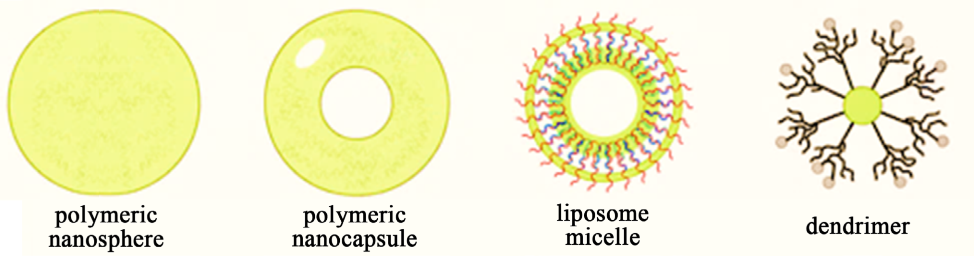

Figure 5. This diagram illustrates the various structures of polymeric and lipid-based nanoparticles used for applications such as targeted drug delivery.

3.3. Carbon-Based Nanoparticles

A broad class of nanomaterials with at least one dimension less than 100 nanometers, carbon-based nanoparticles are mostly made of carbon atoms. Because of their special qualities, which include excellent electrical conductivity, mechanical strength, and thermal stability, they can be used in a variety of industries, including electronics, medicine, and energy. Graphene, fullerenes, and carbon nanotubes are typical examples.

3.3.1. Fullerenes

A special type of carbon-based nanoparticles known as fullerenes has a definite spherical or cage-like shape. One of the most well-known fullerenes is the C60, a molecule made up of 60 carbon atoms shaped like a soccer ball and nicknamed "buckyball". There are twenty hexagons and twelve pentagons in this unusual geometry. In 1985, a group of scientists led by Harold Kroto, Robert Curl, and Richard Smalley made the initial discovery of fullerenes. They went on to receive the Nobel Prize for their efforts. A new area of study in carbon chemistry was made possible by their discovery. Fullerenes have a special structure that makes them very stable and adaptable to a variety of uses. They can be added to materials to improve their electrical characteristics, loaded with additional atoms, or utilized as antioxidants in medicinal research [27].

3.3.2. Carbon Nanotubes (CNTs)

Like a rolled-up sheet of graphene, carbon nanotubes (CNTs) are cylindrical nanostructures made of carbon atoms organized in a hexagonal lattice. They are a material of tremendous interest in many different sectors because of their amazing qualities. Their remarkable mechanical strength is a crucial feature; they are among the stiffest and strongest materials available [28]. They also have exceptional electrical conductivity, acting as either a metal or a semiconductor depending on their "chirality" (the manner in which the graphene sheet is rolled), and high thermal conductivity, effectively transmitting heat down their length. Because of their special qualities, they can be utilized in a variety of ways, such as reinforcing materials in composites to produce lightweight, strong items, or acting as extremely effective wires in electronics and parts of different sensors [29].

3.3.3. Graphene

A single, two-dimensional sheet of carbon atoms organized in a hexagonal, honeycomb lattice makes up the remarkable material known as graphene. According to Neto *et al.* (2009), it is the basic building component of other carbon allotropes, including graphite, fullerenes, and carbon nanotubes [30]. Because of its amazing qualities, graphene is referred to as a "wonder material". With a tensile strength more than 200 times that of steel, it is the strongest substance known to science. Additionally, it is more electrically and thermally conductive than copper [31]. It is a breakthrough material for many applications because of these special qualities as well as its transparency and flexibility. It is being investigated for application in composites, where it can greatly improve the mechanical and electrical qualities of other materials, flexible displays, and high-speed electronics (**Figure 6**) [32].

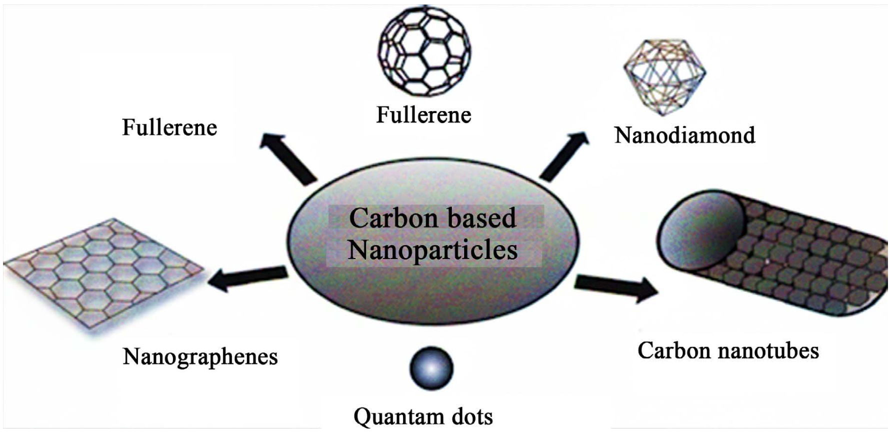

Figure 6. This image displays various types of carbon-based nanoparticles, including nanographenes, fullerenes, nanodiamonds, and carbon nanotubes, all of which are used in a wide range of scientific applications.

4. Synthesis of Gold Nanoparticles

Numerous methods, such as chemical, physical, and biological processes, are used to create gold nanoparticles [33]. The most common method is still chemical synthesis, and different chemical processes have been successfully used to manufacture different types of gold nanoparticles.

4.1. Chemical Synthesis Methods

Chemical synthesis is the most common approach, utilizing a reducing agent to convert gold salt precursors into neutral gold atoms, which then aggregate into nanoparticles.

4.1.1. The Turkevich Method (Modified by Frens)

This is a widely used protocol for producing spherical AuNPs with diameters typically between 10 and 100 nm. It involves the reduction of gold salts using trisodium citrate. The citrate serves a dual purpose: it acts as a reducing agent and a stabilizing agent. By adjusting the ratio of gold to citrate, researchers can control the final particle size; higher citrate concentrations stabilize smaller particles more quickly [34].

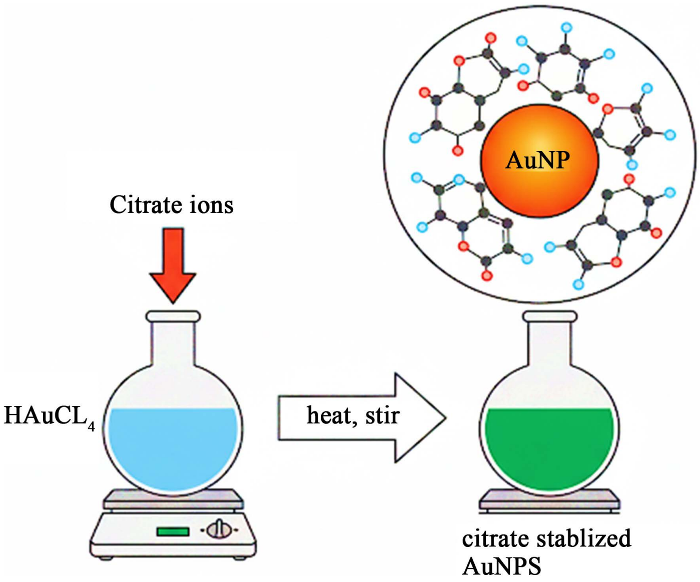

Figure 7. Schematic representation of the Turkevich method for synthesizing citrate-stabilized gold nanoparticles.

4.1.2. The Brust-Schiffrin Method

Developed in 1994, this technique is preferred for synthesizing very small AuNPs (1.5 to 5 nm) that are stable under heat and air. This is a two-phase system. Gold salts are transferred from an aqueous solution to a toluene phase using a phase-transfer agent (TOAB) [35]. Upon adding the reducing agent ($NaBH_4$) in the presence of dodecanethiol, the organic phase turns from orange to deep brown, signaling the formation of low-disparity nanoparticles [36].

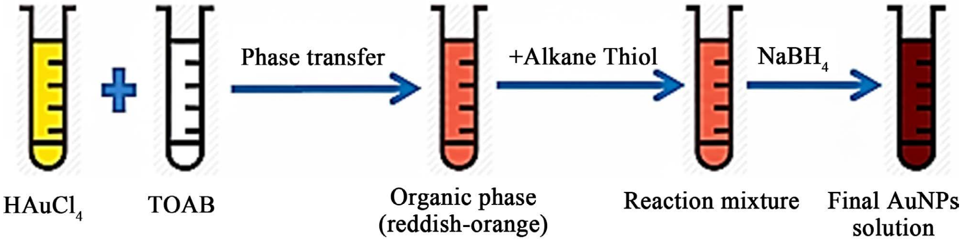

Figure 8. This diagram illustrates the synthesis of gold nanoparticles via the Brust-Schiffrin method, which involves the reduction of gold salts in a two-phase system.

4.1.3. Seeded Growth Method

This method is chosen when a highly controlled size distribution is required for particles between 5 and 40 nm. It is a two-step process. First, small "seed" particles are produced using a strong reducing agent like sodium borohydride ($NaBH_4$). These seeds then act as templates for further growth when added to a metal salt solution. The final size is determined by precisely adjusting the ratio of seeds to the metal salt (**Figure 9**) [37].

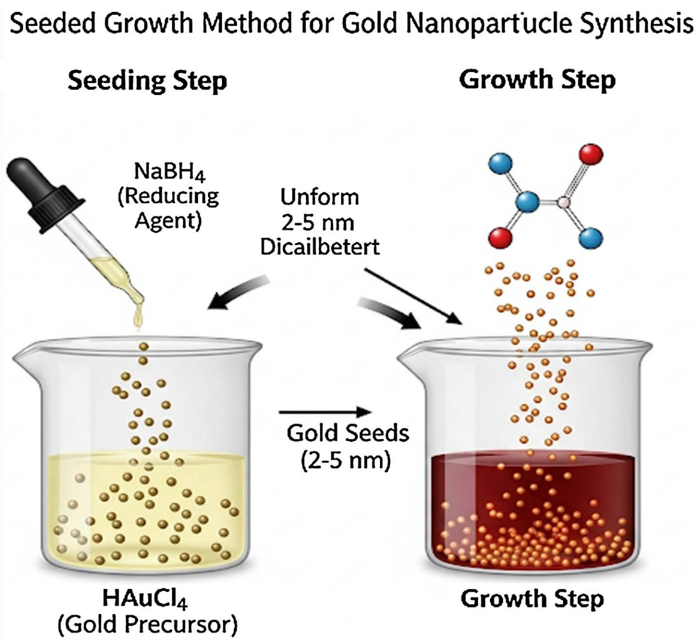

Figure 9. This diagram illustrates the seeded growth method for gold nanoparticle synthesis, a two-step process that allows for the controlled production of uniformly sized nanoparticles.

4.2. Physical and Hybrid Methods

These methods often rely on physical energy rather than chemical reactions alone to produce high-purity particles.

Laser Ablation: A "bottom-up" physical process in which a pulsed laser irradiates a solid gold target submerged in liquid. This method is valued for its ability to precisely regulate nanoparticle characteristics without chemical byproducts.

Microwave Irradiation: Uses electromagnetic waves to heat a reaction mixture rapidly and evenly from the inside out. This leads to much shorter reaction times and often a more uniform product compared to traditional external heating.

4.3. Biological (Green) Synthesis

This approach focuses on sustainability and biocompatibility by using natural extracts instead of harsh chemicals. It utilizes microorganisms (bacteria, fungi) or plant extracts (from leaves, fruits, or seeds). Organic acids and proteins naturally present in these biological materials act as the reducing and stabilizing agents to form the nanoparticles.

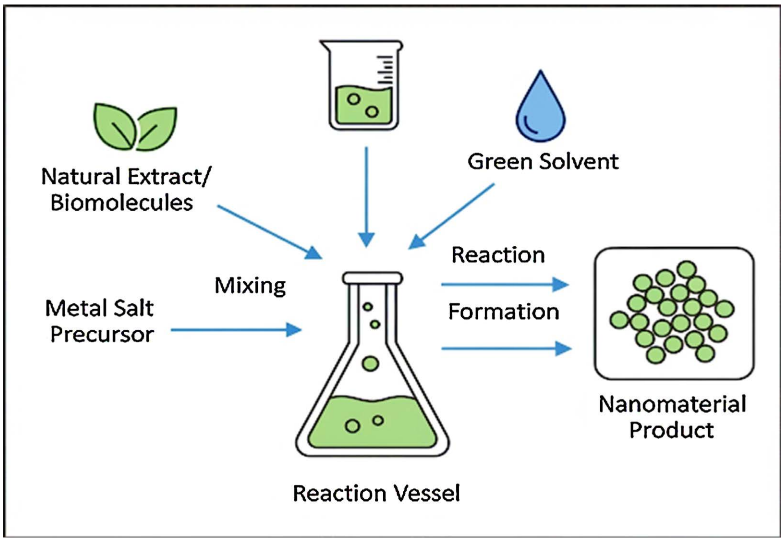

Figure 10. A diagram showing how to make nanomaterials using a safe, green method. It combines a natural material, a metal salt, and a green solvent to create the final product.

5. Characterization of Gold Nanoparticles

Different nanoparticles can be analyzed using a variety of methods, such as atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning electron microscopy (SEM), UV-Vis spectroscopy, XRD, and zeta potential analysis. The size, shape, crystalline structure, surface area, and surface chemistry of gold nanoparticles can all be examined using these techniques [38].

5.1. Spectroscopic and Optical Techniques

Nanoparticles can be effectively characterized and analyzed using spectroscopic and optical methods. These methods use the way light and matter interact to reveal important details about the size, shape, concentration, and surface characteristics of the nanoparticles.

5.1.1. Spectroscopy in the UV-Vis

One highly helpful method for characterizing nanoparticles is UV-Vis spectroscopy. Different materials absorb different wavelengths of light, including ultraviolet, infrared, and visible light. This results in a spectrum, which is a graph that displays the strength of radiation absorbed or emitted by the sample as a function of wavelength. Depending on the diameter of the particle, the absorption peak of gold nanospheres typically occurs between 510 and 550 nm [39].

Surface plasmon resonance causes two peaks to appear in the longitudinal and transverse directions of the nanorod absorbance curve. A nanosphere typically displays a single peak. The absorption peak shifts to a longer wavelength with increasing particle size. The UV-Vis spectra verify that both nanospheres and nanorods were successfully synthesized, as seen in **Figure 11**. The average size of the nanoparticles can be calculated using mathematical theories by tracking these patterns and gathering data on absorption.

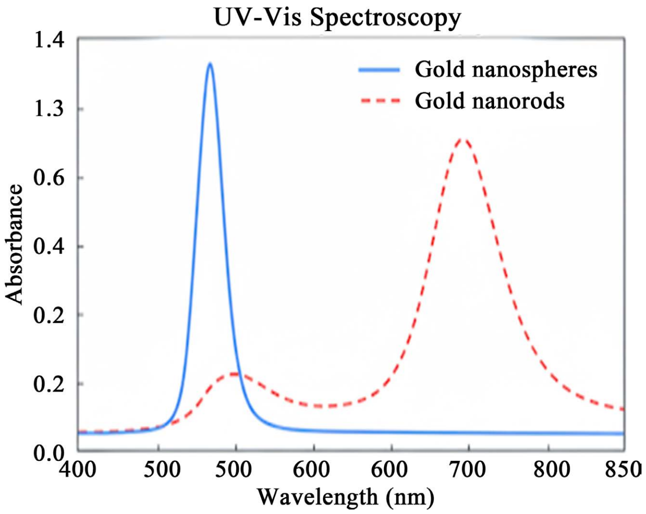

Figure 11. This diagram shows that gold nanospheres absorb light at around 520 nm, while gold nanorods absorb light at around 690 nm due to their different shapes.

5.1.2. X-Ray Diffraction (XRD)

A strong, non-destructive method for determining the crystal structure of materials, including gold nanoparticles, is X-ray diffraction (XRD). By directing an X-ray beam toward a crystalline sample, the technique operates on the basis of Bragg's Law. A detector measures the distinct pattern that is produced when the X-rays diffract from the material's atomic planes at particular angles. In a "fingerprint" for the material's crystal structure, this pattern is shown in a graph known as a diffractogram [40]. By displaying distinctive peaks at anticipated angles, the diffractogram for gold nanoparticles verifies their particular face-centered cubic (FCC) crystal structure.

5.1.3. Zeta Potential Analysis

An essential measure for determining the electrostatic potential at a particle's shear plane in a colloidal dispersion is the zeta potential (ζ). It is a crucial indicator of the colloidal stability of nanoparticles in a system and shows the effective electric charge on the particle surface. A variety of methods can cause nanoparticles in a liquid to acquire a surface charge, creating an "electrical double layer" around the particle [41]. When exposed to an electric field, the closely coupled ions and particle move as a single entity at the zeta potential, which is the boundary of this fixed layer. Figure 12 shows how this double layer is built and the zeta potential that results.

5.2. Microscopy and Imaging Techniques

Spectroscopic and optical techniques are powerful tools used to characterize and analyze nanoparticles. They rely on the interaction of light with matter to provide valuable information about the nanoparticles' size, shape, concentration, and surface properties.

5.2.1. Transmission Electron Microscopy

Electrons are used in the transmission electron microscope (TEM). According to

Erni *et al.* (2018), a TEM, which uses an electron as its light source, has a resolution hundreds of times higher than a light microscope [42]. Using these high-resolution photos and software, the average diameter of gold nanoparticles may be determined, and their size distribution quantitatively examined (**Figure 13**). Using this expensive technology, one may estimate the size and precise shape of the nanoparticle by producing high-resolution, highly magnified photographs [43].

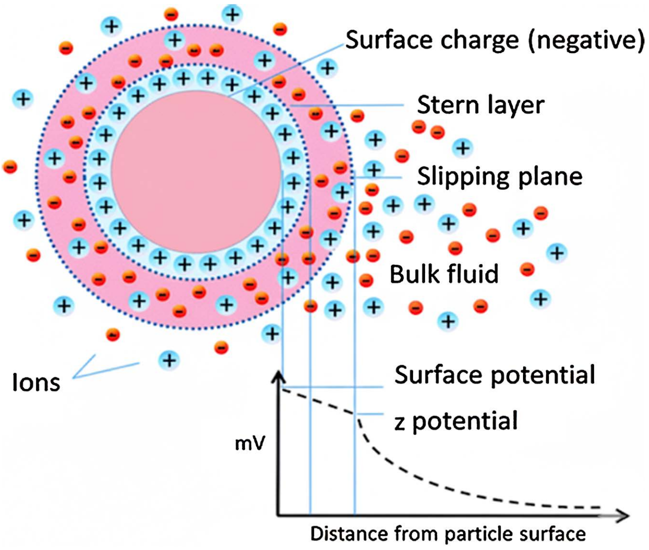

Figure 12. This diagram explains Zeta Potential, which is the charge on the surface of a particle in a liquid. A high zeta potential indicates a stable suspension, where particles remain separate, while a low potential means they will likely clump together.

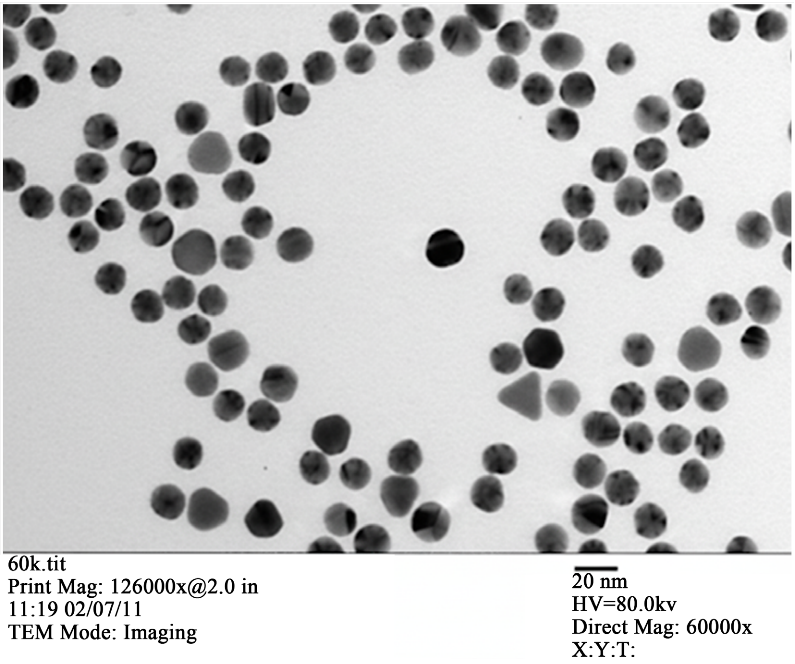

Figure 13. Transmission Electron Microscopy (TEM) image of gold nanoparticles. The image shows that the particles are spherical and have a size of approximately 20 nm, as indicated by the scale bar.

5.2.2. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is regarded as the gold standard for identifying or characterizing nanoparticles, along with transmission electron microscopy. High-resolution images of the nanoparticles produced using this method can be used to determine a number of significant characteristics, including size, shape, size distribution, and surface structure [44]. SEM and TEM operate in a similar way (**Figure 14**). The collision of the concentrated beam causes the specimen to release its own electrons, which are then captured by a detector to produce a high-resolution microscopic image. SEM makes it possible to measure multiple samples at once. Both TEM and SEM are expensive techniques for describing a nanoparticle's form [45].

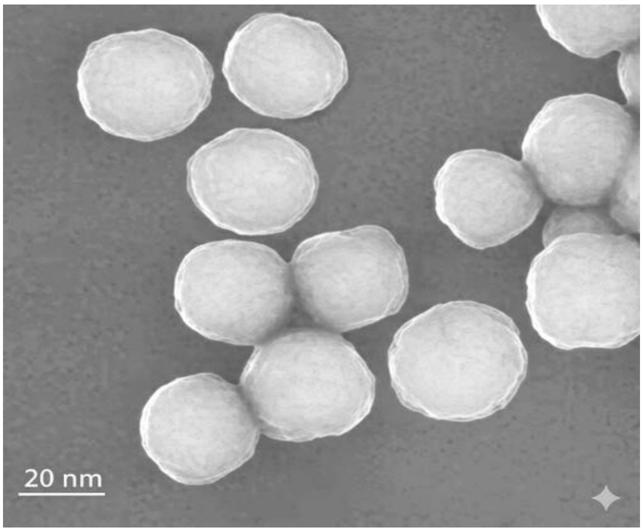

Figure 14. This image is a Scanning Electron Microscopy (SEM) image of gold nanoparticles. It shows that the particles are mostly spherical and around 20 nm in size, as indicated by the scale bar.

5.2.3. Atomic Force Microscopy (AFM)

Atomic force microscopy uses a closed-loop laser beam alteration system, in which a laser beam is redirected from an AFM lever or cantilever onto a position-detecting sensor. A photodetector detects the reflected beam's altered location due to the cantilever's bending caused by interacting forces. The magnitude of the probe's movement can be ascertained by measuring the movement of the laser spot on the image detector. High-resolution images and precise topographical data about the material are produced as a result. AFM measurements are conducted using specialized modes [46].

6. Application of Gold Nanoparticles

Applications for gold nanoparticles in medicine are numerous and include photothermal cancer therapy and tailored drug delivery. Their distinct optical and electrical characteristics make them useful in advanced electronics, biosensing, and diagnostics. All applications are mentioned in detail below:

6.1. Gold Nanoparticles as Sensors

Due to their unique optical properties and exceptional sensitivity, gold nanoparticle (AuNP) sensors are widely used in a wide range of fields. Their primary application is biosensing, which facilitates rapid and accurate disease diagnosis. When AuNPs are functionalized with specific antibodies or DNA probes, they can detect traces of infections, viruses, and disease biomarkers in patient samples, making them a promising platform for point-of-care diagnostics [47].

AuNP-based sensors are utilized in the food industry to ensure safety by detecting toxins, allergens, and infections [48].

6.2. Gold Nanoparticles as Catalysts

Although gold in bulk is often inert, gold nanoparticles' exceptionally high surface-to-volume ratio and special electrical characteristics make them highly catalytically active. A process known as catalysis occurs when a material accelerates a chemical reaction without being consumed. Since AuNPs are in a different phase than the reactants, they function as efficient heterogeneous catalysts. Their size has an inverse relationship with their catalytic activity; the smaller the particle, the more catalytically active it is [49]. AuNPs work especially well in reactions where dangerous compounds are changed into less dangerous ones. Using sodium borohydride to reduce 4-nitrophenol to 4-aminophenol is a well-known example. AuNPs catalyze this process, which would otherwise proceed very slowly. To improve their stability and surface area, they are frequently supported on materials such as alumina (Al_2O_3), which increases their effectiveness and affordability for industrial and environmental applications [50].

6.3. Gold Nanoparticles in Biomedical Applications

Because of their distinct physical characteristics and biocompatibility, AuNPs offer a wide range of uses in biomedical science beyond their particular functions in drug delivery and cancer.

Gold nanoparticles (AuNPs) are effective contrast agents for a variety of imaging modalities, such as Computed Tomography (CT) scans and X-ray imaging, because of their high electron density [51]. Additionally, AuNPs can be functionalized with targeting ligands to accumulate precisely in tumors, making them an effective tool for monitoring cancer treatment and diagnosis [52]. When compared to conventional drugs that spread throughout the body and are rapidly eliminated, this tailored method offers a substantial benefit.

Gold Nanoparticles in Human Cancer Treatment

By addressing some of the main drawbacks of conventional medicines, nanotechnology presents a viable strategy for the treatment of cancer. Because AuNPs may be designed to target tumor cells specifically, they are especially effective. Once within the tumor, they may perform a variety of tasks.

1) Photothermal Therapy (PTT)

Photothermal therapy (PTT), a minimally invasive cancer treatment, uses light to generate heat in order to precisely target and kill tumor cells. It employs materials known as photothermal agents, of which gold nanoparticles (AuNPs) are an excellent illustration. AuNPs can be used as effective photothermal agents in the form of nanorods and nanoshells because they can absorb near-infrared (NIR) light, which can penetrate biological tissues deeply without causing damage.

When these AuNPs build up in a tumor, usually through bloodstream injections and by passively collecting in the tumor's leaky blood arteries, a harmless NIR laser is pointed at the location [47]. As a result, the tumor's temperature rises to over 42˚C (107.6˚F) as the nanoparticles transform the absorbed light energy into intense local heat. Thermal ablation from this focused heating kills the cancer cells while sparing the healthy tissue around them. Because of its accuracy and low level of invasiveness, PTT is a very promising method of treating cancer [53].

2) Radiation Therapy

Radiation therapy can be made much more effective by using gold nanoparticles (AuNPs), a process called radiosensitization. Because of their high atomic number (Z = 79), they are significantly more effective at absorbing X-ray radiation than the body's soft tissues. When a tumor containing AuNPs is exposed to a high-energy X-ray beam, the nanoparticles absorb a disproportionately high quantity of the radiation [54]. A series of physical phenomena follow this absorption, mainly among them the emission of low-energy photons and secondary electrons.

3) Drug Delivery

Gold nanoparticles (AuNPs) use a "guided missile" strategy to treat cancer, making them efficient drug delivery vehicles. Conventional chemotherapy medications frequently cause serious systemic adverse effects like nausea, hair loss, and destruction of healthy cells since they circulate throughout the body. However, AuNPs can be functionalized, which means that certain molecules can bind to their surface [55]. This procedure enables them to be coated with targeted ligands, including antibodies, that are intended to bind selectively to receptors on the surface of cancer cells after being loaded with chemotherapeutic medications [56].

6.4. Gold Nanoparticles in Water Purification

Gold nanoparticles are being investigated as a viable and efficient water cleaning method. Their application provides a benefit over traditional techniques, which are frequently wasteful and energy intensive. Gold nanoparticles (AuNPs) are very efficient catalysts, especially when used in environmental applications such as pollution degradation. Their remarkably high surface-area-to-volume ratio and distinct electronic structure at the nanoscale are the sources of their catalytic power [57]. Because of these characteristics, they can speed up a reaction without being spent by lowering its activation energy. The vast surface area of gold nanoparticles (AuNPs) allows them to adsorb and remove a variety of pollutants, including heavy metal ions, from water, making them extremely useful in environmental remediation. The adherence of atoms, ions, or molecules from a liquid or gas onto a surface is known as adsorption. Pollutants, including mercury, lead, and cadmium, can attach to AuNPs in large quantities due to their high surface-area-to-volume ratio [58].

6.5. Gold Nanoparticles as Cosmeceuticals

The gold nanoparticles, also known as nano cosmeceuticals, are being utilized in dermatological and cosmetic products due to the special qualities of AuNPs. Enhanced transport: because gold nanoparticles (AuNPs) may greatly enhance the transport of active substances into the skin, their usage in dermatology and cosmetics is growing. The stratum corneum, the outermost layer of the skin, serves as a strong barrier that inhibits the absorption of numerous active substances [59]. Because of their nanoscale size, AuNPs are able to get past this barrier more successfully than larger molecules. They serve as microscopic transporters, delivering anti-aging peptides, antioxidants (such as vitamins C and E), and other advantageous substances deep into the dermis and epidermis [60]. Due to their potent antioxidant properties and capacity to promote collagen synthesis, gold nanoparticles (AuNPs) are utilized in anti-aging lotions [61]. A reduction in collagen, which causes wrinkles and a loss of elasticity, is a common sign of aging skin. Additionally, oxidative stress from free radicals, which are produced by environmental variables like pollution and UV radiation, accelerates aging. AuNPs are naturally able to neutralize these free radicals, shielding the skin and avoiding cellular harm. They are a powerful component of anti-aging formulas because of their dual function of encouraging collagen synthesis and offering antioxidant protection.

6.6. Gold Nanoparticles in Agriculture

Recent agricultural research has focused on gold nanoparticles (AuNPs), which hold great promise for sustainable and effective farming. Their main application is as targeted delivery nanocarriers, and they are made through a sustainable process termed biosynthesis.

Agriculture could greatly benefit from the application of gold nanoparticles (AuNPs) in terms of sustainability and productivity. Their use as nano carriers for the targeted administration of insecticides, fertilizers, and herbicides is one of their main uses. This strategy tackles a significant flaw in conventional spraying techniques, which frequently result in significant waste and damage to the environment due to evaporation and runoff [62]. The AuNPs can be designed to bind to soil particles or target plant tissues precisely by encapsulating active chemicals. By drastically lowering the quantity of pesticides needed for efficient pest control or nutrient supply, this targeted delivery strategy minimizes agriculture's environmental impact while also enhancing crop health and output [63].

7. Challenges and Limitations in AuNP Development

Despite the significant potential of gold nanoparticles (AuNPs) in various sectors,

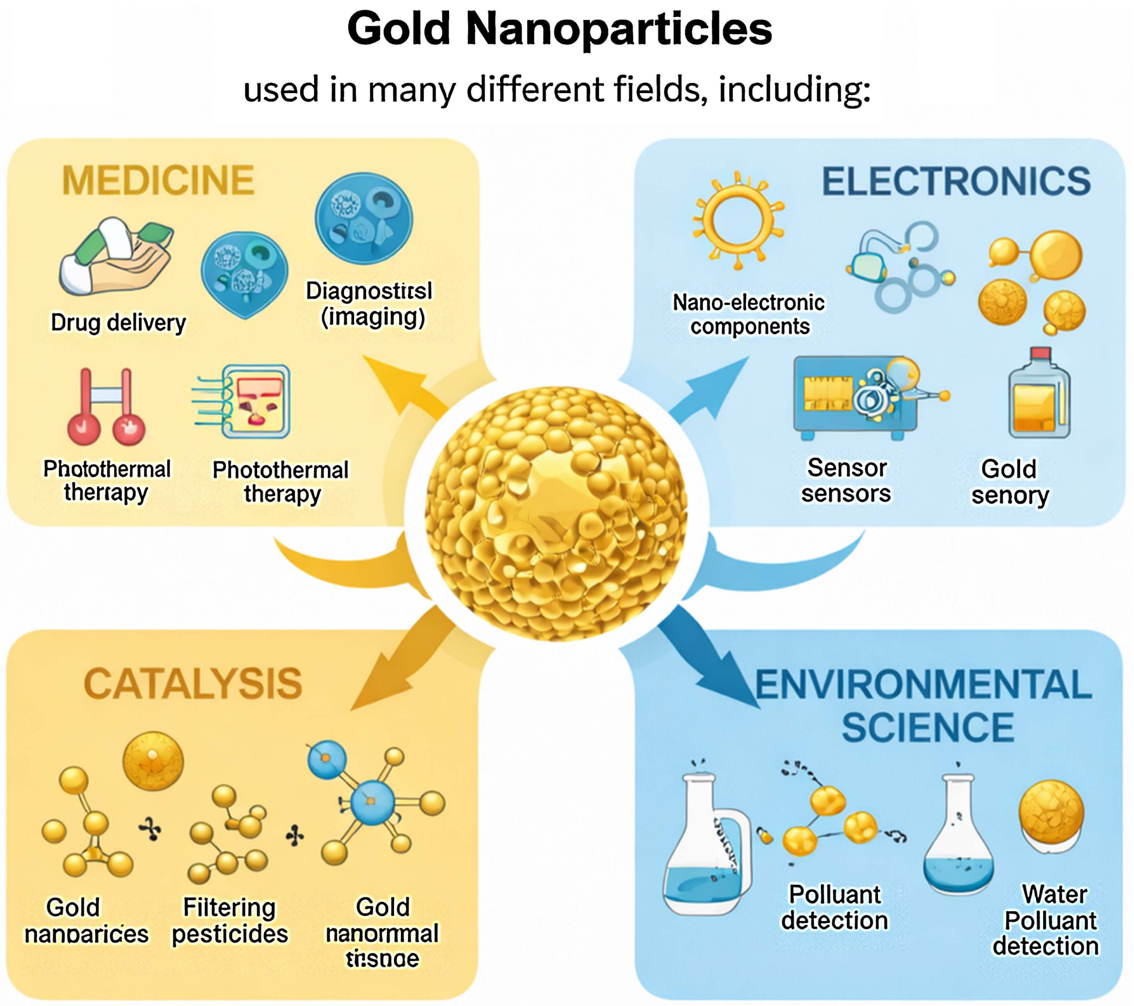

Figure 15. This picture shows how gold nanoparticles are used in many different fields, including medicine, electronics, catalysis, and environmental science.

several practical challenges and "bottlenecks" currently limit their widespread commercial and clinical adoption.

7.1. Scalability and Reproducibility

One of the primary technical hurdles is the transition from small-scale laboratory synthesis to large-scale industrial production.

- Batch-to-Batch Consistency: Many chemical synthesis methods, such as the Turkevich or seeded growth protocols, are highly sensitive to minor variations in temperature, stirring speed, and concentration. Scaling these up often leads to a loss of control over size distribution and shape uniformity, which are critical for applications such as biosensing and medical imaging.
- Cost of Production: While gold in bulk is expensive, the high energy requirements of physical methods (such as laser ablation) and the cost of specialized stabilizing ligands make large-scale production economically challenging compared to traditional materials.

7.2. Long-Term Stability and Biological Fate

The stability of AuNPs in complex environments is a major concern, particularly for biomedical applications.

- Aggregation in Biological Fluids: When introduced into the human body, AuNPs often encounter high concentrations of proteins and salts that can cause them to clump together (aggregate). This aggregation changes their optical properties and can alter their intended biological function.
- The "Protein Corona": Once in the bloodstream, AuNPs are immediately coated by a layer of proteins, known as a protein corona. This "biological identity" can mask the targeting ligands on the particle's surface, preventing them from reaching the desired tumor or tissue.
- Bioaccumulation: Although gold is chemically inert, the long-term fate of AuNPs in the body—specifically their potential to accumulate in the liver and spleen—remains a subject of ongoing research, as the body lacks a natural mechanism to break down or easily excrete inorganic nanoparticles.

7.3. Regulatory and Ethical Hurdles

The path from the laboratory to the market is heavily governed by regulatory bodies such as the FDA or EMA.

- Lack of Standardized Protocols: There is currently a lack of standardized international protocols for characterizing and testing the safety of nanomaterials. This creates uncertainty and delays in the approval process for new nano-based drugs and devices.
- Complexity of Safety Evaluations: Because the toxicity of AuNPs can change based on their size, shape, and surface coating, each new formulation requires its own exhaustive and expensive series of clinical trials, which often discourages commercial investment.

8. Nontoxicity and Safety Profile of Gold Nanoparticles

While gold nanoparticles (AuNPs) are widely celebrated for their biocompatibility and chemical inertness in bulk form, their interaction with biological systems at the nanoscale is complex and necessitates a thorough toxicological evaluation. Nanotoxicity refers to the potential of these materials to induce adverse biological effects, which are significantly influenced by their physicochemical properties.

8.1. Factors Influencing Toxicity

The safety profile of AuNPs is not universal, but depends on several critical parameters:

- Size: Smaller nanoparticles (typically <10 nm) often exhibit higher toxicity than larger ones because they can more easily penetrate cellular membranes, enter the nucleus, and interact with DNA or proteins.
- Shape: The morphology of AuNPs (e.g., spheres vs. rods or stars) affects how

they are internalized by cells. For instance, nanorods may exhibit different uptake kinetics and potential membrane disruption compared to spherical nanoparticles.

- Surface Coating and Charge: The functionalization of AuNPs plays a pivotal role in their safety. Positively charged surface coatings often demonstrate higher cytotoxicity due to their strong affinity for negatively charged cell membranes, whereas neutral or PEGylated surfaces are generally better tolerated by the body.

8.2. Mechanisms of Toxicity

When toxicity does occur, it is often mediated through the generation of Reactive Oxygen Species (ROS). High concentrations of AuNPs can induce oxidative stress, leading to inflammation, mitochondrial dysfunction, and potential cell death. Furthermore, their high surface-to-volume ratio increases their reactivity with biological molecules, which can lead to unintended protein "coronas" that alter the particle's biological identity and distribution within the body.

9. Future Perspectives and Conclusion

Advanced Computational Integration and AI

The next frontier in AuNP research lies in the integration of Artificial Intelligence (AI) and Machine Learning (ML) to move from trial-and-error experimentation to predictive modeling.

- Predicting the Protein Corona: Future research should focus on ML algorithms capable of predicting the composition of the nanoparticle-protein corona in various biological fluids. By inputting the nanoparticle's size, shape, and surface charge, AI can model how specific plasma proteins will adsorb, allowing researchers to design "stealth" coatings that avoid immune detection and prevent premature clearance by the liver.
- Optimizing Synthesis for Specific LSPR Peaks: AI can be utilized to automate the optimization of synthesis parameters. By analyzing vast datasets, ML models can predict the exact concentrations of reagents and reaction times needed to achieve a specific Localized Surface Plasmon Resonance (LSPR) peak. This is particularly valuable for developing tailored contrast agents for photothermal therapy that must absorb light at specific "biological window" wavelengths.
- High-Throughput Screening: The combination of microfluidics and AI will allow for the rapid screening of thousands of functionalization combinations, identifying the most effective gold-ligand pairings for targeted drug delivery with minimal toxicity.

10. Summary

As this review has explored, gold nanoparticles represent a pinnacle of nanotechnological advancement, bridging ancient artistry with modern clinical science. While challenges regarding scalability, long-term bio-stability, and regulatory hurdles remain, the transition toward green synthesis and the incorporation of predictive AI modeling offer a clear roadmap for the future. By refining the synergy between synthesis techniques and specific end-use applications, AuNPs will continue to redefine the boundaries of medicine, environmental science, and beyond.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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