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Review

Various Methods of Synthesis and Applications of Gold-Based Nanomaterials: A Detailed Review

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ABSTRACT: Gold-based nanoparticles (Au NPs) have emerged as essential materials in nanotechnology due to their unique optical, electronic, and catalytic properties. This Review explores the synthesis, functionalization, and broad spectrum of applications of Au NPs. Key synthesis methodologies, such as chemical reduction and green synthesis, are discussed with a focus on how they influence nanoparticle size, shape, and stability. Surface functionalization techniques that enhance biocompatibility and target specificity are examined in detail. The versatile applications of Au NPs in biomedicine, ranging from diagnostic imaging and targeted drug delivery to cancer therapy through hyperthermia, underscore their utility in modern healthcare. Furthermore, Au NPs' superior conductivity and manufacturability drive innovations in electronic applications, including sensors, conductive inks, and nanoelectronics for next-generation devices. In environmental science, their efficacy in detecting pollutants and purifying water is highlighted, representing a promising avenue for ecological applications. Collectively, these applications demonstrate the dynamic role of gold-based nanoparticles across multiple fields, emphasizing the need for continued research and innovations to harness their potential and address current challenges.

1. INTRODUCTION

Gold-based nanoparticles (Au NPs) have attracted much interest in the past few years due to their size-dependent distinct physical, chemical, and biological characteristics different from those of the macroscopic material.[1] The development of such an introduction should focus on increasing the awareness of the various synthesis methods of Au NPs, their properties and uses in different fields including medicine, electronics, and environmental management.[2] Yes, it is possible to use Au NPs in fact; however, the scientific research about them began later. Without doubt, the most famous usage had been the staining of glasses and ceramics with gold colloids among the Romans, with an example being the Lycurgus Cup.[3] Detailed scientific research on gold colloids only began in the 19th century with Michael Faraday and built up to modern nanoscience and nanotechnology.[4] Several Faraday experiments untangled the optical properties of gold colloids and their interaction with light to produce a characteristic red or purple coloration.[5] Au NP synthesis has been accomplished via physical, chemical, and biological methods, allowing control over particle size, shape, and surface chemistry.[6] The most common is the reduction of chemical entities from various gold salts, for example, $HAuCl_4$ in an aqueous solution, in the presence of reducing agents such as sodium citrate or ascorbic acid.[7] This method can be used to tune nanoparticle size by controlling the concentration of the reducing agent and reaction conditions.[8] Examples of physical methods include laser ablation, which refers to the high-energy laser beam-induced ablation of a gold target immersed in a liquid medium. In the process, the size and shape of the produced nanoparticles are controlled.[9] Biological methods using plant extracts, microorganisms, or enzymes are an alternative and cleaner way. Acting as both reducing and stabilizing agents, these biological entities help synthesize biocompatible nanoparticles.[10] Au NPs possess a lot of unique properties, because the application is so versatile: optical properties with many unique features due to surface plasmon resonance are one of these.[11] This property arises from a phenomenon where the conduction electrons on the gold surface oscillate in resonance with the incident light.[12] Such a property gives a strong absorption and scattering of light, which can be tuned by alteration of size, shape, and the surrounding environment of the nanoparticles.[13] Au NPs are suitable catalysts in most chemical reactions since they have high surface area and contain active sites that include oxidation and reduction

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processes.[14] Their biocompatibility is intrinsic to their ability to be easily functionalized with any biomolecule-peptides, proteins, or DNA-hence suitable for different biomedical applications.[15] The unique properties of Au NPs are associated with significant technological advances in integrations, such as those in medicine,[16] electronics,[17] and environmental science.[18] The applications of Au NPs in biomedicine include diagnostic imaging, drug delivery[19] and photothermal therapy.[20] Their tunable optical properties[21] and the ability to go through biological barriers enable their use for imaging with targeted treatment of cancer.[22] The electrical conductivities of Au NPs are very important in the creation of high-end electronic devices, which include sensors and conductive inks.[23] On the other hand, Au NPs find application in environmental monitoring[24] and remediation due to their stability and catalytic properties in pollutant degradation[25] and optical properties in the detection of contaminants.[26] Electrocatalysis refers to the acceleration of electrochemical reactions through the use of a catalyst, often enhancing the efficiency of processes like fuel cells, batteries, and water splitting.[27−31] Au NPs have gained significant attention in electrocatalysis due to their unique electronic properties, high surface area, and biocompatibility. These properties enable Au NPs to effectively facilitate redox reactions, making them ideal for applications in energy conversion, environmental sensing, and renewable energy technologies. Their tunable size and surface chemistry further enhance their catalytic performance in various electrochemical processes. On the other hand, Au NPs degrade a group of dyes and pollutants through photocatalytic and catalytic processes with the potentials for creating sustainable wastewater treatment solutions and cleanup of the environment.[32−34] For the literature review, data was collected from the *Web of Science* database to explore treatment-based research on Au NPs. Over 14 653 research articles have been published from 2015 up to March 2024. The publication count remained high until 2021, but there is a sharp dropoff in publications from 2022 onward. This indicates that Au NPs research was of high interest in previous years, with a possible shift in funding allocations in more recent years.

2. GOLD AND GOLD-BASED NANOPARTICLES

Gold is a significant transition metal with distinct properties that lead to wide use in various fields.[35] Of these features, the most striking are its extraordinary malleability,[36] resistance against tarnish and corrosion, and high electrical conductivity.[37] Such features make gold a perfect material for electronic elements, high-precision connectors, and applications in advanced medical devices.[17] Its biocompatibility and chemical stability are also very important in medical and biochemical areas.[38] Gold nanoparticles have risen to prominence in nanotechnology because of their unique optical, electronic,[38] and catalytic features.[39] Because of the very high surface-to-volume ratio, 0D gold nanoparticles are also highly effective in catalysis and sensing applications.[40] This becomes an essential feature for drug delivery systems and biosensors where nanoparticles interact with biomolecules.[41] Gold nanorods, 1D materials with unique optical characteristics based on surface plasmon resonance and altered by the aspect ratio, are equally crucial in photothermal therapy, imaging, and electronics. Their outstanding electrical conductivity is suitable for applications in nanoscale circuits and other nanoelectronic devices as well.[42] The 3D structures in gold, including nanoporous gold and composites of gold, offer better mechanical and electronic properties. The high surface area, together with the increased conductivity renders these structures well-poised for energy storage devices, including batteries and supercapacitors.[43] Besides, the gold-based heterojunctions and alloys have found novel applications in the domains of photonics and spintronics.[44,45] Their unique properties are harnessed for advanced technology applications.

Gold-based nanostructures form an exciting material class that finds applications in diverse disciplines. These nanomaterials possess extraordinary properties, which have been developed toward different interests as metals, semiconductors, and nonmetals; natural or synthetic polymers; ceramics; and others. Au NPs are added into metal nanocomposites to improve mechanical, electrical, and thermal properties and optimize the performance of metal-based electronic, catalytic, and sensing materials.[46] On doping or modifying semiconductors with designed electronic and optical properties, gold nanoparticles can be used in several applications dealing with optoelectronics,[47] photovoltaics,[48] and sensors.[49] Au NPs, when combined with nonmetals such as carbon nanotubes or graphene, respectively enhance their conductance, mechanical strength, and adsorption capacity of the materials, paving the way for potential use in energy storage,[50] environmental remediation,[51] and biological and medical applications.[52] On the other hand, Au NPs developed within polymeric matrices offer antimicrobial activity, biocompatibility, and mechanical reinforcement to intelligent materials designed for healthcare,[53] packaging, and textiles use.[54] In ceramics, Au NPs function as sintering aids or additives,[55] bringing serious enhancements in densification and mechanical features along with thermal stability in the performance of the ceramic materials and, therefore, in their performance in applications that include electronic devices, aerospace components, and thermal barrier coatings. These are synthesized from chemically reduced, sol—gel, and green synthesis methods and are promising in a vast area of applications, such as antimicrobial coatings, sensors, photoelectric devices, and environmental cleanup. In this manner, gold-based nanostructures find application across multiinterdisciplinary problems in current-day materials science and engineering.

3. SYNTHESIS METHODS OF GOLD NANOPARTICLES

A variety of methods for the synthesis of gold nanoparticles are available, with each offering unique advantages and applications. Some of the standard techniques include chemical reduction, green synthesis, and growth through seed mediation. Other more advanced techniques, including laser ablation and plasma synthesis, provide control over the characteristics of the nanoparticles. The methods depend on factors such as the required size, shape, and surface properties of the nanoparticles.

3.1. Chemical Reduction Method.

The reducing agents cause metal ions to reduce into nanoparticles, providing a way to accurately control their size and distribution. Therefore, Zhao and Friedrich addressed the synthesis of Au NPs by citrate and sodium borohydride ($NaBH_4$) reduction methods. The differences in some experimental parameters that influence the synthetic method and several means of scaling up production are discussed. The study also dramatically focuses on the purification of the nanoparticles by dialysis for their improved quality and applicability.[56] Mostafavi and Ghanavi addressed the synthesis of Au NPs that involve human serum albumin (HSA) as a reducing agent. It is a process in which electrons are transferred from albumin's carboxylic groups to $AuCl_4^-$ ions to form Au NPs. Water was involved as the primary solvent during the process. The experiment employs 0.01% $HAuCl_4$ solution and recognized manufacturers of HSA. This controlled reduction process points out the promising applications of Au NPs in nanomedicine, nanobiotechnology, and

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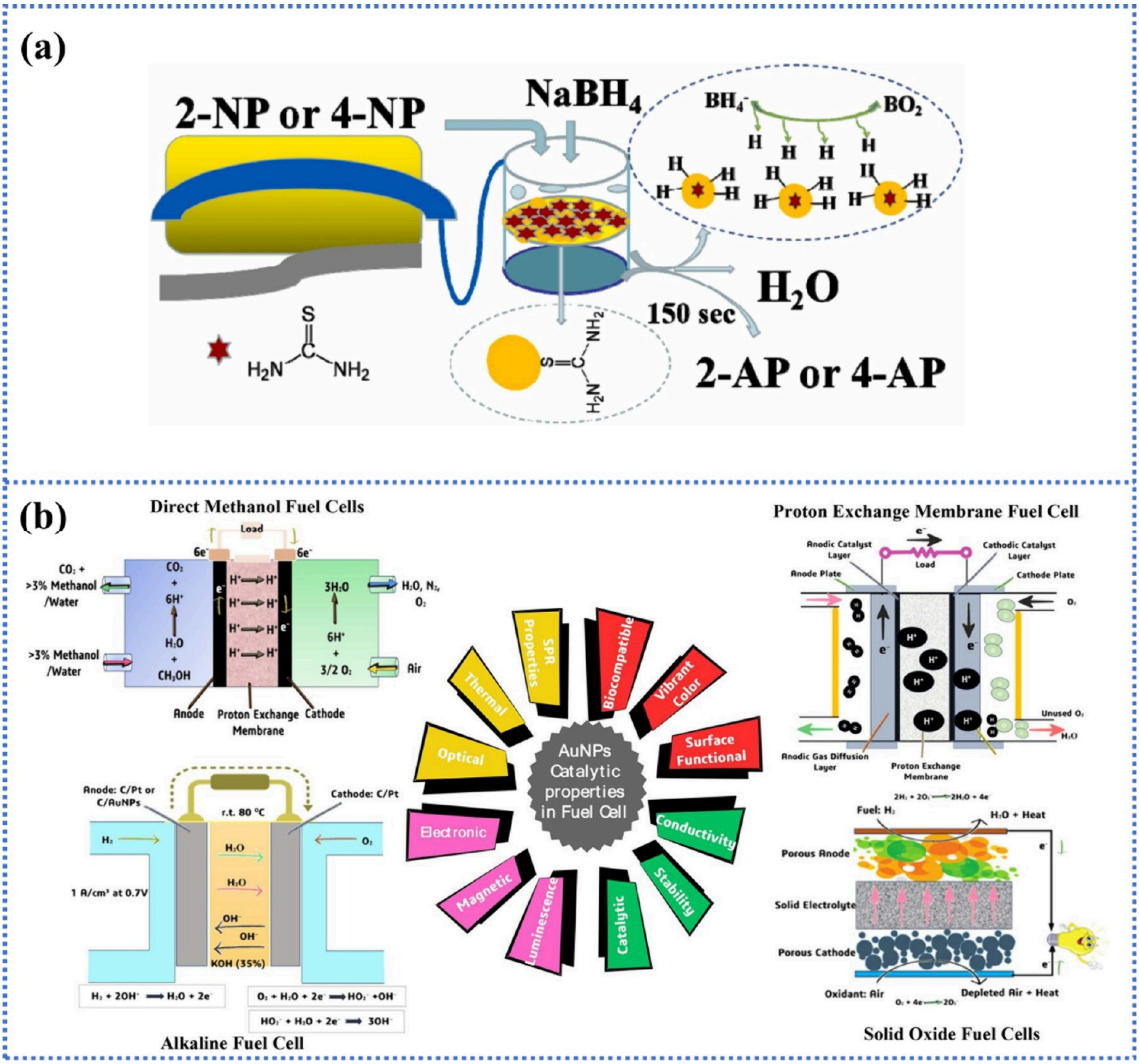

Figure 1. (a) Application of a stable gold nanoparticle film prepared via chemical reduction method supported by thiourea as an effective catalyst on nitrophenol reduction in water. [Reproduced with permission from ref 59. Copyright 2024, Elsevier.] (b) Gold nanoparticles synthesis through chemical reduction method as an active catalyst for efficient oxygen reduction in fuel cells: perils and prospects. [Reproduced with permission from ref 60. Copyright 2023, Elsevier.]

advanced spectroscopy.[57] Doan et al. focused on synthesizing Au NPs via the chemical reduction process by extracting *Litsea cubeba* (LC) fruits. Fresh LC fruits were washed, dried, and powdered before soaking in distilled water at 90 °C. The extract was mixed with $HAuCl_4$ solution under vigorous stirring in darkness, whereas the color change signified successful synthesis. Factors such as the concentration of gold ions, reaction time, and temperature are optimized using ultraviolet−visible spectrophotometry. This enhances the effectiveness of LC fruit extract in the chemical reduction method for synthesizing Au NPs.[58] Furthermore, Xia et al. developed a simple and efficient method for treating nitrophenol using thiourea-treated Au NPs films fabricated via filtration. The Au NP film, with a nanoporous structure, exhibited excellent catalytic activity, reducing 1.0 mM 2-nitrophenol to 2-aminophenol in just 150 s. The optimal concentrations of thiourea and $NaBH_4$ were 20 μg/mL and 1000 mM, respectively. The Au NP films maintained high catalytic efficiency (90%) after seven cycles, offering a promising industrial strategy for reducing nitrophenol in wastewater treatment (Figure 1a).[59] Sandhu et al. explored the use of Au NPs as efficient catalysts for the oxygen reduction reaction (ORR) in fuel cells, driven by the need for sustainable energy solutions. Au NPs have gained attention for their electrochemical properties, stability, and potential as alternatives to platinum, which face high costs and limited durability. The study examines the influence of particle size, morphology, and alloying with other metals on catalytic performance while addressing challenges like resistance to poisons and stability. This Review provides insights into enhancing Au NP catalysts, paving the way for their use in fuel-cell technology as a high-performing, sustainable energy solution (Figure 1b).[60] Table 1 presents various gold-based nanomaterials synthesized through the chemical reduction method. These nanomaterials exhibit diverse characteristics, such as varying sizes, shapes, and surface modifications, which contribute to their distinct catalytic, optical, and electronic properties.

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Table 1. Various Au-Based Nanomaterials Synthesized via Chemical Reduction Methods

sample	name of material	morphology of material	applications	ref
01	Au nanorods	rod-shaped	biomedical imaging	61
02	Au nanospheres	spherical	drug delivery	62
03	Au clusters	star-shaped	photo thermal therapy	63
04	Au nanocubes	cubic	catalysis	64
05	Au nanoshells	core−shell	cancer treatment	65
06	Au nanowires	wire-like	electronic devices	66
07	Au nanoflowers	flower-shaped	sensing applications	67
08	Au nanoplates	plate-like	surface-enhanced Raman spectroscopy	68
09	Au nanobelts	belt-shaped	envirnomental monitoring	69
10	Au nanorods	dot-shaped	optical devices	70

3.2. Green Synthesis of Au NPs. Green synthesis of Au NPs is a procedure in which naturally available material, like plant extracts, is used as a reducing agent for forming Au NPs. In addition to being eco-friendly, Au NP synthesis is much less expensive than other noble-metal nanoparticles, because the use of toxic chemicals in the synthesis process is minimized. Fahad et al. conducted an experiment with two main objectives: to synthesize gold nanoparticles using the seed extract of *Pistacia chinensis* and to explore their biological activities. In this method, gold salt ($HAuCl_4$) was reduced using a plant extract. The study also sought to evaluate the enzyme inhibitory, analgesic, and sedative potential of the synthesized nanoparticles. This research, finally, aims at developing a method for the green synthesis of Au NPs with potential therapeutic applications.[71] Li et al. carried out research work whose primary objectives included synthesizing Au NPs via a green synthesis approach, using Mentha longifolia leaf extract, and characterizing these synthesized nanoparticles. The preparation of the aqueous extract of *Mentha longifolia* leaves was carried out by the respective method. The extract was added dropwise into an aqueous solution of $HAuCl_4$ with continuous stirring at room temperature until light yellow or red wine. A color change indicated the formation of Au NPs. The resulting nanoparticles were recovered by centrifugation, thoroughly washed with deionized water, and dried. The study is a quest to develop a green approach for synthesizing Au NPs.[72] Furthermore, Vorobyova et al. synthesized Au NPs from plum peel extract using betaine-urea and choline chloride-urea deep eutectic solvents, which exhibited higher reducing ability than traditional solutions. The Au NPs, characterized by ultraviolet-visible light (UV-vis) spectroscopic analysis, Fourier transform infrared (FTIR) spectroscopy, and scanning electron microscopy-X-ray diffraction (SEM-XRD), showed significant antioxidant and antibacterial activity, with the cream containing 0.5% Au NPs improving skin moisturization (Figure 2a).[73] In another study, Xie et al. synthesized a green gold-

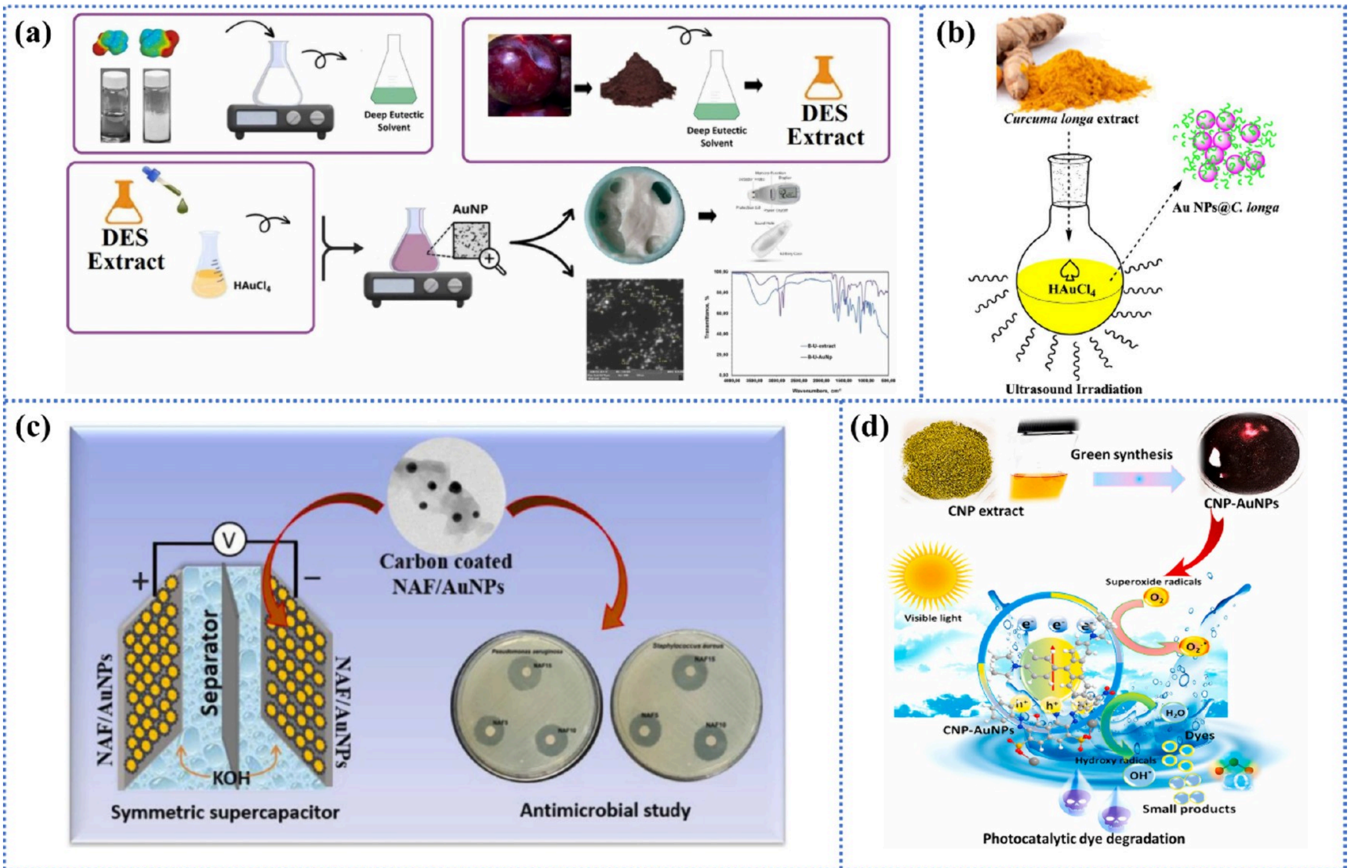

Figure 2. (a) Au NP synthesis using green solvents and a plum waste extract. [Reproduced with permission from ref 73. Copyright 2024, Elsevier.] (b) Ultrasound assisted synthesis of Au NPs@C. longa mediated by Curcuma longa extract. Ultrasound-mediated green synthesis of Au NPs by using root and rhizome extract of *Curcuma longa* and investigation dialysis application for dye pollutant reduction, growth-enhancing activity some worms previously described On is an animal suffering from osteoarthritis at the knee joints. [Reproduced with permission from ref 74. Copyright 2024, Elsevier.] (c) Green synthesis of Nyctanthes arbor-tristis flower-decorated gold nanoparticles: Sustainable methods for enhanced antimicrobial and supercapacitor applications. [Reproduced with permission from ref 75. Copyright 2024, Elsevier.] (d) A simple and eco-friendly method for synthesizing gold nanoparticles using Canthium parviflorum (CNP) extract, enabling sustainable and energy-efficient photocatalytic degradation of organic pollutants for environmental cleanup. [Reproduced with permission from ref 18. Copyright 2024, Elsevier.]

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based nanocatalyst (Au NPs@C. longa) using *Curcuma longa* extract under ultrasonic conditions for environmental remediation. The catalyst effectively reduced organic dyes like Methyl Orange, Methylene Blue, and 4-nitrophenol, with excellent activity, kinetics, and stability, and also showed promising results for chondrogenesis and functional recovery in osteoarthritis models by regulating redox homeostasis and reducing inflammation (Figure 2b).[74] Furthermore, Sobi et al. synthesized Au NPs using Nyctanthes arbor-tristis flower extract, revealing their potential for antibacterial and energy storage applications. The NAF-derived Au NPs showed significant antibacterial activity against *Pseudomonas aeruginosa* and exhibited excellent performance in a symmetric supercapacitor, with a specific capacitance of 64 F g^{-1} and 97% cycling stability after 5000 cycles (Figure 2c).[75] Additionally, Kumar et al. green-synthesized Au NPs, using Canthium parviflorum (CNP) leaf extract, demonstrating high photocatalytic efficiency in degrading brilliant green and amido black 10B dyes (83.25% and 86%) under visible light. The CNP-Au NPs also showed rapid 4-nitrophenol reduction (89.4%), with enhanced photocatalytic activity due to improved charge separation and active site formation, making them effective for wastewater treatment (Figure 2d).[18] These studies highlight the versatility and effectiveness of green-synthesized Au NPs derived from various plant extracts for a range of applications, including environmental remediation, antibacterial treatments, energy storage, and biomedical interventions. The synthesized Au NPs demonstrate significant potential for improving both industrial processes and therapeutic outcomes, offering sustainable, cost-effective solutions for a variety of challenges.Table 2 summarizes various gold-based nanoparticles synthesized using the green synthesis approach. These nanoparticles are derived from eco-friendly methods involving natural resources, such as plant extracts and microorganisms, which offer advantages such as cost-effectiveness, sustainability, and reduced environmental impact.

Table 2. Various Au-Based Nanoparticles Synthesized via Green Synthesis Approach

sample	source of extraction	morphology of material	applications	ref
01	aloe vera extract	spherical	antimicrobial, catalytic	76
02	turmeric extract	triangular	antioxidant, anti-cancer	77
03	neem leaf extract	spherical	antimicrobial, anti-oxidant	78
04	green tea	rod-shaped	catalytic, anti-cancer	79
05	mango peel	cubic	antimicrobial, catalytic	80
06	cinnamon bark	triangular	antimicrobial, anti-cancer	81
07	banana peel	hexagonal	antimicrobial, catalytic	82
08	lemon peel	spherical	antimicrobial, anti-oxidant	83
09	orange peel	rod-shaped	antimicrobial, catalytic	84
10	guava leaf	spherical	antimicrobial, anti-cancer	81
11	tulsi leaf	triangular	antimicrobial, anti-oxidant	85
12	papaya leaf	spherical	antimicrobial, anti-cancer	86
13	basil leaf	hexagonal	antimicrobial, anti-oxidant	87

3.3. Hydrothermal Synthesis of Gold Nanoparticles. Hydrothermal synthesis involves high temperatures and pressures within the aqueous medium to prepare Au NPs. The process allows for better regulation of the particle size and morphology, proving to be quite helpful in many applications in nanotechnology. For instance, Vinay et al. synthesized Au NPs from spider cobweb using a hydrothermal method and characterized them by XRD, UV-vis, SEM, energy-dispersive X-ray analysis (EDAX), and transmission electron microscopy (TEM). The Au NPs showed excellent photocatalytic activity in degrading Rhodamine B and Methylene Blue dyes, attributed to enhanced light sensitivity and reduced electron−hole recombination (Figure 3a).[88] Furthermore, Neha et al. described the synthesis of Au NPs incorporated into ZnO/rGO heterostructures for sunlight-driven photocatalysis (SPC). Pure ZnO nanostructures, ZnO/rGO binary nanocomposites (BNCs), and ZnO/rGO/Au ternary nanocomposites (TNCs) were synthesized hydrothermally. The study mentioned that photodegradation increased substantially in the presence of Au NPs due to the effective charge transfer. Among all the tested materials, TNCs have shown the highest photodegradation efficiency for Methylene Blue dye, compared to ZnO and BNCs, facilitating enhanced electron migration and charge separation.[89] In another study, Rehman et al. synthesized Au NPs from alkaline protease derived from *Phalaris minor* seed extract, demonstrating excellent photocatalytic degradation of Methylene Blue (100% in 30 min) under visible light. The ALPs-Au NPs also showed significant antibacterial activity against *S. aureus* and *E. coli*, along with 88% antioxidant activity, indicating strong potential for environmental and medical applications (Figure 3b).[90] The hydrothermal synthesis method proves to be a highly effective approach for producing Au NPs with a controlled size, morphology, and enhanced properties. By utilizing high temperature and pressure in an aqueous medium, this method facilitates the creation of nanoparticles with improved photocatalytic activity, charge transfer efficiency, and antibacterial properties. The versatility of hydrothermal synthesis allows for its application in various nanocomposite systems, making it a promising method for developing nanoparticles for both environmental and medical applications.

3.4. Synthesis of Gold NPs via Coprecipitation Method. The coprecipitation method for synthesizing Au NPs involves the simultaneous precipitation of gold ions with a reducing agent, often in the presence of stabilizing agents to control particle size and dispersion. This method typically requires mixing a gold precursor, such as chloroauric acid ($HAuCl_4$), with a reducing agent like sodium borohydride ($NaBH_4$) in an aqueous solution, resulting in the formation of Au NPs. For instance, Yazid et al. prepared Au NPs on zinc oxide via the deposition−precipitation method. The synthesis involved the preparation of a solution of gold(III) chloride, which was further heated to 80 °C; the solution was then adjusted to the desired levels of pH using a NaOH solution. Zinc oxide was then dispersed within the solution, which resulted in the pH change compensated by dropwise HCl addition to keep the pH constant. The suspension was stirred for 2 h, washed, and filtrated to remove the impurities and further dried and calcined at 450 °C to convert the gold precursors to their metallic form. This method resulted in Au NPs with diameters less than 5 nm and has been repeated at various pH levels to probe the effects on both gold loading and particle size distribution.[91] Furthermore, Compagnoni et al. prepared Au NPs on a TiO_2 support using a modified deposition−precipitation method, using urea and $NaBH_4$ as chemical reductants. This process involved the dispersion of TiO_2 in water containing urea, followed by adding a $NaAuCl_4$ solution, stirring, and reduction with $NaBH_4$. The aim is to prepare Au/TiO_2 catalysts with very low metal loading.[92] In another example, Su G et al. synthesized Au NPs supported on TiO_2 from electronic waste using the deposition−precipitation with urea (DPU) method. Characterization by SEM and HR-TEM confirmed the successful synthesis of well-distributed Au NPs on TiO_2. Temperature-programmed reduction (TPR) results showed lower activation temperatures, likely due to NiO species from gold coating separation, which may enhance H_2 spillover on TiO_2. UV-vis DRS revealed a redshift in the localized surface plasmon resonance (LSPR) with increasing temperature, demonstrating the potential of Au/TiO_2 NPs for CO oxidation and adding value to electronic waste recycling (Figure 4).[93] This method can be considered adequate because it continuously synthesizes nanoparticles showing the desired characteristics and is, thus, a reliable and reproducible technique.Table 3 presents various gold-based nanomaterials synthesized through the coprecipitation method. This method involves the precipitation of gold ions in the presence of stabilizing agents, yielding

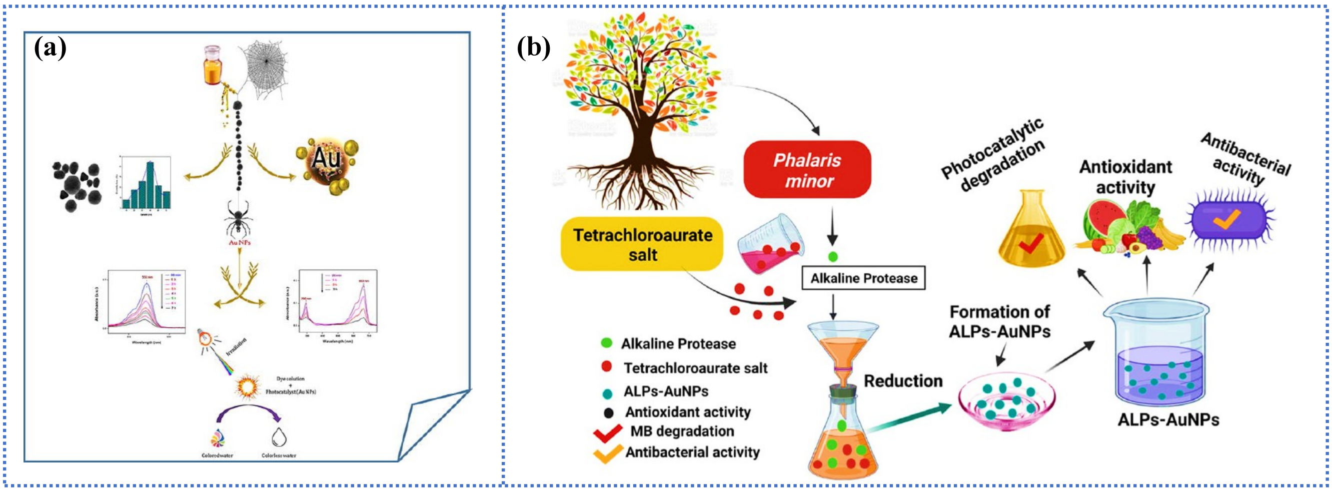

Figure 3. (a) Hydrothermal production of Au NPs utilizing spider web as an innovative biomaterial: application in photocatalysis. [Reproduced with permission from ref 88. Copyright 2020, Elsevier. (b) Hydrothermal synthesis of novel gold nanoparticles functionalized with alkaline protease (ALPs-Au NPs): a fresh approach to photocatalytic and biological applications. [Reproduced with permission from ref 90. Copyright 2024, Elsevier.]

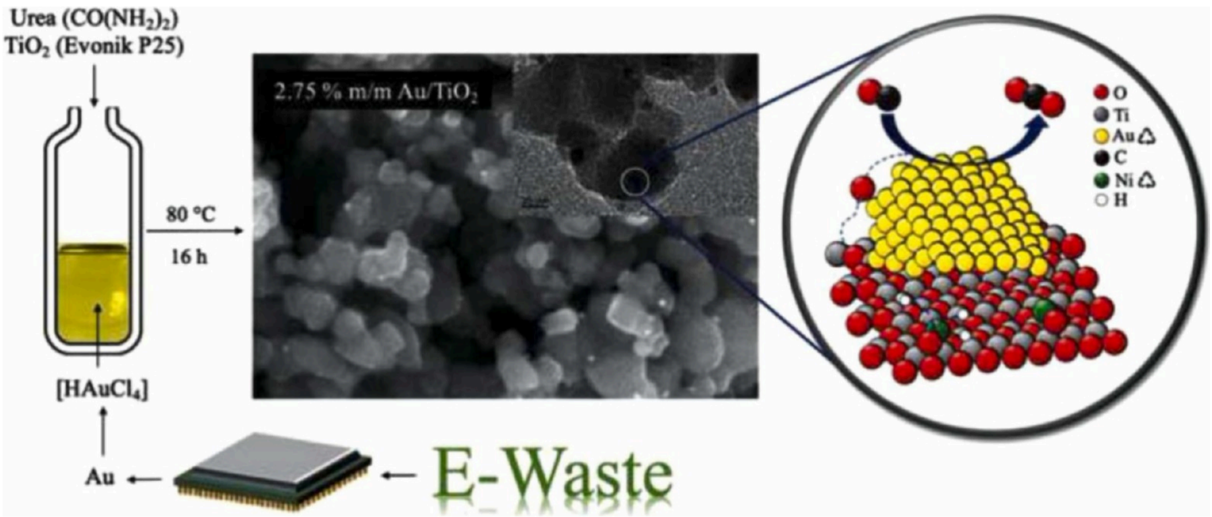

Figure 4. Transforming waste into value: gold nanoparticles derived from e-waste synthesis via a co-precipitation method, supported on TiO_2, as a catalyst for CO oxidation. [Reproduced with permission from ref 93. Copyright 2024, Elsevier.]

nanoparticles with controlled size, morphology, and enhanced properties for a wide range of applications. Future derivations might be focused on fine-tuning the reaction parameters to refine further nanoparticle quality, which will be beneficial for applications in multiple fields.

3.5. Synthesis of Gold NPs via Sol−Gel Methods. The sol−gel method enables the synthesis of Au NPs by hydrolyzing and condensing metal alkoxides to form a gel that subsequently dries and later calcinates. This process made it possible to control the size of the particles and to have uniform particles. In this regard, it is reported that Laura et al. have proposed a one-pot synthetic approach in preparing sol−gel graphite electrodes containing Au NPs. Unlike traditional methods, the sol−gel is used directly to synthesize Au NPs by either chemical or thermal reduction of gold precursors such as $NaAuCl_4$ or $HAuCl_4$. Thus, optimization of the Si/Au molar ratio and reduction conditions will be a crucial parameter to control the material characteristics using this approach. This technique showed practical synthesis for Au NPs with good conductivity and electrocatalytic activity, mainly under thermal reduction, to be used for possible amperometric sensing applications.[114] Au NPs were doped into sodium borosilicate glass by Gao et al. using Au NPs synthesized by a combined sol−gel and atmosphere-controlled heat-treatment process. The formed metallic Au is allowed to flow into the glass matrix using TEOS hydrolysis and the addition of solutions of H_3BO_3, Na, and $HAuCl_4$ to form a wet gel, which is later dried and heat-treated in atmospheres of O_2, H_2, or N_2. The linear and nonlinear optical properties of the obtained monolithic glass with Au NPs were characterized using several spectroscopic and microscopic methods.[115] The synthesis of Au NPs through the sol−gel approach gives a very flexible and effective tool by which fine control over the particle size and distribution is afforded. This technique opens up new avenues with up-and-coming applications in catalysis, electronics, and medical diagnostics. Figure 5 illustrates optical and photocatalytic characteristics of ultrathin sol−gel Au NPs@TiO_2 film.[116] Table 4 highlights various gold-based nanomaterials synthesized via the sol−gel approach. This method offers precise control over the nanoparticle size and composition, making it suitable for fabricating highly uniform and stable gold nanomaterials for diverse applications.

3.6. Microwave-Assisted Technique for the Synthesis of Au NPs. The microwave-assisted method for synthesizing Au NPs is a rapid and energy-saving process that provides uniform heating and higher reaction rates. In this regard, microwave irradiation can be used as the primary source for controlling the size and shape of nanoparticles, thus making this approach very promising, compared to conventional methods. Gutiérrez-Wing et al. synthesized passivated Au NPs using a microwave-assisted process in a two-phase system with 1-dodeca-

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Table 3. Various Au-Based Nanomaterials Synthesized via a Co-precipitation Method

sample	name of material	morphology of material	applications	ref
01	Au NPs	spherical	drug delivery	94
02	gold nanorods	rod-shaped	photothermal therapy	95
03	spherical Au NPs	spherical	cancer imaging	96
04	spherical Au NPs	spherical	catalysis	97
05	cubic Au NPs	cubic	biosensors	98
06	spherical Au NPs	spherical	antimicrobial	99
07	triangular Au NPs	triangular	bio imaging	100
08	spherical Au NPs	spherical	gene delivery	101
09	star-shaped Au NPs	star-shaped	diagnostic tools	102
10	spherical Au NPs	spherical	environmental monitoring	103
11	spherical Au NPs	spherical	SERS (surface-enhanced Raman)	104
12	flower Au NPs	flower-like	chemical sensing	105
13	spherical Au NPs	spherical	water treatment	106
14	hexagonal Au NPs	hexagonal	electrochemical applications	107
15	spherical Au NPs	spherical	anti-inflammatory	108
16	spherical Au NPs	spherical	optical devices	109
17	spherical Au NPs	spherical	energy storage	110
18	platelet-shaped Au NPs	platelet	plasmonic devices	111
19	spherical Au NPs	spherical	bioscaffolds	112
20	spherical Au NPs	spherical	antioxidant activity	113

nethiol; the average particle size was 1.8 nm. XRD identified the self-assembly of the nanoparticles into cubic ordered superstructures from an off-white powder. By XRD analysis it has also shown that *n*-alkanethiols have a protective effect on crystal growth besides contributing to superstructure formation; the distance between the particles is 3.56 nm.[144] Bayazit et al. reported the synthesis of Au NPs by combining single-mode microwave irradiation with microfluidic chemistry. $HAuCl_4$ and trisodium citrate (Na3 Cit) precursors afforded Au NPs particle widths in the range of 4−15 nm and aspect ratios in the range of ∼1.4−2.2 upon microwave irradiation for 90 s.[145] Furthermore, Al-Radadi et al. employed an eco-friendly, plant-mediated approach using olive oil, licorice root, and coconut oil extracts to synthesize gold-coated iron (Fe@Au) nanoparticles via microwave irradiation, enhancing reaction rate and product quality. The Fe@Au NPs, characterized by UV-vis, EDX, XRD, high-resolution transmission electron microscopy (HR-TEM), FT-IR, high-performance liquid chromatography (HPLC), high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM), particle size distribution (PSD), and magnetic hysteresis, demonstrated significant antioxidant activity and were effective against *Helicobacter pylori* and ulcers (Figure 6a).[146] In another study, Marques et al. developed a microwave-assisted, seed-mediated method for the fast, uniform growth of Au NPs onto nanocellulose (NC) membranes, optimizing them as SERS platforms. The NC membranes, with high mechanical strength and surface area, exhibited an enhancement factor (∼106) using Rhodamine 6G, a shelf life of at least 7 months, and were used for label-free detection of SARS-CoV-2 spike protein, demonstrating the potential of Au NPs on NC substrates for sensitive and stable analytical applications (Figure 6b).[147] Additionally, Vandarkuzhali et al. biosynthesized silver (AgNPs) and Au NPs using *Borassus flabellifer* fruit extract under microwave irradiation, characterizing them via UV-vis, XRD, FTIR, dynamic light scattering (DLS), TEM, and X_ray photoelectron spectroscopy (XPS). The Ag NPs (∼7−9 nm) and Au NPs (∼5−7 nm) exhibited efficient dye reduction of Methylene Blue and Congo Red, along with antibacterial and anticancer activity against MCF-7 cells, suggesting their potential as eco-friendly catalysts for dye reduction and biological applications (Figure 6c).[148] Moreover, Joshi et al. developed a one-pot microwave synthesis method for producing polydisperse gold nanoparticles (Au-Mx) with mixed shapes and sizes, achieving broadband localized surface plasmon resonance (SPR) for enhanced light-harvesting efficiency. When incorporated into the photoanode of dye-sensitized solar cells (DSSCs), the Au-Mx nanoparticles improved photoconversion efficiency by ∼30%, demonstrating the effective use of broadband SPR for efficient charge generation in plasmonic devices (Figure 6d).[149] Table 5 presents various gold-based nanomaterials synthesized using the microwave-assisted technique. This method allows for rapid and uniform heating, resulting in high-quality Au NPs with a controlled size and morphology. Microwave-assisted synthesis of Au NPs is rapid, efficient, and environmentally friendly. This gives high-quality nanoparticles enhanced yield and reproducibility due to the control of reaction

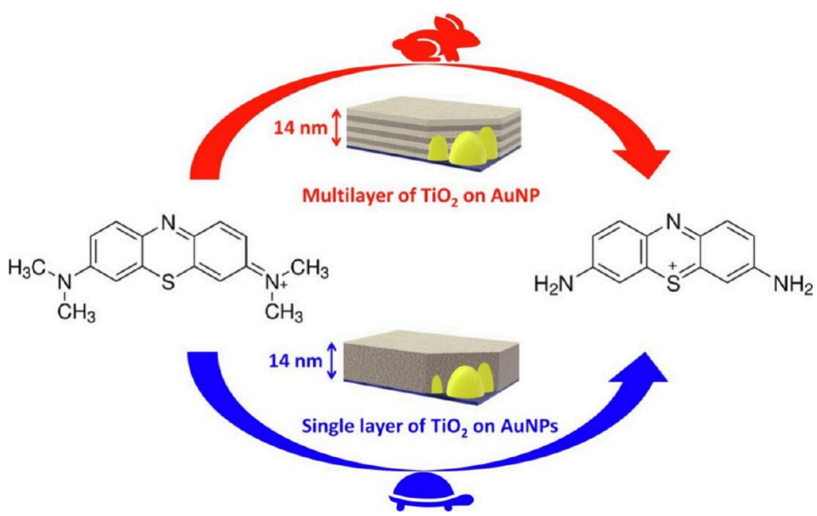

Figure 5. Optical and photocatalytic characteristics of ultrathin sol−gel Au NPs@TiO_2 film. [Reproduced with permission from ref 116. Copyright 2024, Elsevier.]

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Table 4. Various Au-Based Nanomaterials Synthesized via a Sol−Gel Approach

sample	name of material	morphology of material	applications	ref
01	Au NPs	spherical	catalysis, sensing	117
02	Au-Si NPs	core−shell	drug delivery, imaging	118
03	Au@TiO_2 NPs	core−shell	photocatalysis	119
04	Au NPs	rod-shaped	photothermal therapy	120
05	Au-ZnO NPs	composite	anti-bacterial, catalysis	121
06	Au NPs	cubic	electrochemical sensing	122
07	Au@Ag NPs	core−shell	catalysis	123
09	Au−Fe_3O_4 NPs	composite	magnetic separation	124
10	Au NPs	nano clusters	biomedical imaging	125
11	Au@CeO_2 NPs	core−shell	catalysis	126
12	Au NPs	branched	photothermal therapy	127
13	Au-SnO_2 NPs	composite	gas sensing	128
14	Au NPs	nano plates	sensing	129
15	Au@ZrO_2 NPs	core−shell	catalysis	130
16	Au NPs	hollow nanospheres	drug delivery	131
17	Au-SiO_2 NPs	composite	imaging, drug delivery	132
18	Au NPs	nanowires	electronics	133
19	Au@TiO_2 NPs	core−shell	photocatalysis	119
20	Au NPs	hexagonal	catalysis, sensing	134
21	Au-MnO_2 NPs	composite	catalysis	135
22	Au NPs	triangular	surface-enhanced Raman	136
23	Au@CuO NPs	core−shell	photo catalysis	137
24	Au NPs	nanoribbons	electronics	138
25	Au-graphene NPs	composite	sensing	139
26	Au NPs	polyhedral	catalysis	140
27	Au@Al_2O_3 NPs	core−shell	catalysis	141
28	Au NPs	porous	drug delivery	142
29	Au@ZnO NPs	core−shell	antibacterial, catalysis	143
30	Au NPs	nanorods	photothermal therapy	95

parameters. The technique holds promise on a large scale with numerous applications in the biomedical, catalytic, and electronic areas.

3.7. Laser Ablation Method for the Synthesis of Au NPs. The laser ablation method for making Au NPs involves the use of high-energy laser pulses for ablating a gold target submerged in a liquid medium. The technique provides ultrapure Au NPs without employing chemical reagents. At the same time, one attains fine control over the particle size and distribution, which leads to the development of Au NPs with unique optical and electronic properties, making this method quite effective for diverse biomedical and industrial applications. For instance, Hettiarachchi et al. utilized pulsed laser ablation in liquids (PLAL) with a microchip laser (MCL) system to synthesize Au NPs in aqueous solutions, with and without poly(*N*-vinyl-2-pyrrolidone) (PVP) surfactant. The study highlighted that gas bubbles formed during ablation reduced NP formation efficiency, particularly in high-viscosity solutions, and suggested that PVP chain length did not affect NP size or ablation efficiency, while the short pulse duration of the MCL system contributed to consistent NP size by limiting bubble growth (Figure 7a).[166] Furthermore, Jaber et al. synthesized SrNPs via laser ablation in liquids, decorated them with Au NPs, and incorporated the mixture into glass ionomer cement to enhance antibacterial properties and fracture resistance. The study demonstrated that the addition of Au NPs/Sr NPs significantly improved antibacterial activity against *Streptococcus mutans*, reduced surface roughness, and increased compressive strength from 370 N to 600 N, with characterization by XRD, FTIR, TEM, and atomic force microscopy (AFM) revealing near-spherical nanoparticles (10−50 nm) and enhanced material properties (Figure 7b).[167] Additionally, Jelić et al. synthesized Fe−Au bimetallic nanoparticles using pulsed laser ablation in liquid, comparing picosecond and nanosecond laser pulses. They found that the picosecond laser produced monomodal particles (70 ± 30 nm), while the nanosecond laser generated bimodal particles (7 nm and ∼1 μm), with different particle formation mechanisms that were attributed to laser melting and fragmentation in liquid (Figure 7b).[168] Wender et al. reported on preparing reproducibly stable Au NPs by laser ablation of gold foil within and outside of four different ionic liquids. The authors found that ablating gold foil inside ILs, including BMI·BF4, BMI·PF6, and (BCN)MI·NTf2, provided nonspherical Au NPs in the range of 5−20 nm. In contrast, when using BMI·N(CN)2, flower-like Au NPs of ∼50 nm were obtained. The size and shape of the nanoparticles were highly conditioned by the foil's location-inside or outside the IL. The behavior was due to the variation of nucleation and growth conditions at the IL surface or within the IL, thus indicating the critical role of the chemical composition of the IL, in addition to the IL/air interface in stabilizing the Au NPs during laser ablation.[169] Khumaeni et al. produced pure colloids of Au NPs by using low-power Nd-laser ablation at a wavelength of 1064 nm. The pulsed laser beam (7 ns, 30 mJ) is directed and focused on a high-purity gold sheet positioned in deionized water, which produces a dark-red colloid of GNPs. The GNPs obtained were nearly spherical with a mean diameter of 23.5 nm and a standard deviation of 6.4 nm, thus exhibiting a characteristic surface plasma resonance at 520 nm. The setup carried out the experiment under periodic agitation of the gold sheet and the solution to make a homogeneous colloid. This is a practical measure for synthesizing highly pure GNPs with well-defined size and morphology.[170] The laser ablation method used to create Au NPs is environmentally friendly, as it does not require any reagents and allows for reasonable control over the size and shape of the nanoparticles. Table 6 summarizes various gold-based nanomaterials synthesized through the laser ablation method. This technique utilizes high-energy laser pulses to ablate a gold target in a liquid medium, resulting in the formation of nanoparticles with unique size distributions and surface characteristics. This technique typically produces highly pure Au NPs with interesting optical properties, making it potentially useful in various fields such as biomedicine, electronics, and materials science.

3.8. Microemulsion Method for the Synthesis of Au NPs. The synthesis of Au NPs by the microemulsion method is used as a versatile and efficient way to capitalize on the unique characteristics of the microemulsions being used as nanoreactors. Particle size and distribution, which are important for a wide range of applications from medicine to electronics, can be controlled excellently by utilizing this technique. By fine-tuning the composition of the microemulsion, researchers can produce special requirements for the characteristics of the Au NP. A new method for biocompatible Au NP synthesis in a microemulsion system is presented. It involves the reduction of Au(III) ions by $NaBH_4$ in a microemulsion, resulting in monolayer-protected Au NPs with monohydroxy-alkylated PEG as the ligand. The 7−9 nm Au NPs were characterized by UV-visible spectrophotometry, TEM, and DLS. The present results demonstrate that these particles are stable and do not show toxicity toward HeLa cells. This allows for the easy production of stable, water-soluble Au NPs that can be used for various biological applications.[186] Bandyopadhyaya and coworkers reported Au NPs synthesis through the microemulsion method using a water-in-oil (W/O) emulsion. From their study, the mean hydrodynamic diameter of GNPs was found to increase with the molar ratio of water and dioctyl sodium sulfosuccinate (AOT), hence showing a clear correlation between initial water drop diameter and nanoparticle size.[187] Table 7 highlights various gold-based nanomaterials synthesized using the microemulsion method. This approach involves the use of surfactant-stabilized water-in-oil or oil-in-water microemulsions, which provide a

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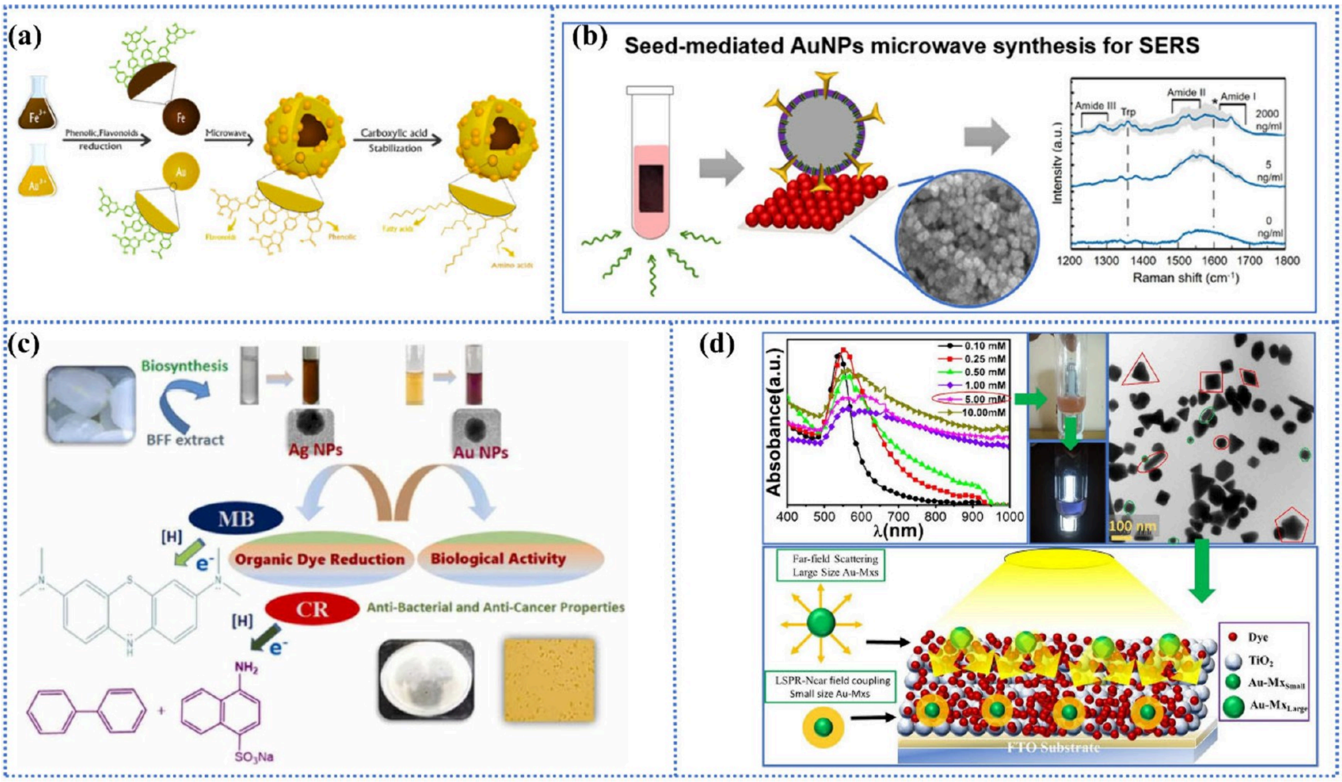

Figure 6. (a) Eco-friendly microwave-assisted synthesis of Fe@Au core−shell magnetic nanoparticles aimed at boosting olive oil's effectiveness in eliminating *Helicobacter pylor*. [Reproduced with permission from ref 146. Copyright 2022, Elsevier.] (b) Microwave-assisted bottom-up seed-mediated growth of gold nanoparticles on nanocellulose to improve stability and maximize performance in SERS applications. [Reproduced with permission from ref 147. Copyright 2021, Elsevier.] (c) One-pot microwave synthesis of irregular gold Have-assisted biosynthesis of silver and gold nanoparticles using *Borassus flabellifer* fruit for dye reduction, antibacterial, and anticancer activities. [Reproduced with permission from ref 148. Copyright 2021, Elsevier.] (d) One-pot microwave synthesis method for producing polydisperse gold nanoparticles (Au-Mx) with mixed shapes, sizes, and its performance. [Reproduced with permission from ref 149. Copyright 2022, Elsevier.]

Table 5. Various Au-Based Nanomaterials Synthesized via Microwave-Assisted Technique

sample	name of material	morphology of material	applications	ref
01	Au NPs	spherical	catalysis, biomedicine	150
02	Au nanorods	rod-shaped	drug delivery	151
03	Au nanospheres	spherical	sensing, photothermal	152
04	Au nanocubes	cubic	antibacterial, electronics	153
05	branched gold nanoparticles (B−Au NPs)	branched	environmental remediation	154
06	Au nanoflowers	flower-like	bio sensing	155
07	Au nanostars	star-shaped	imaging	156
08	hexagonal Au NPs	hexagonal	catalysis, drug delivery	157
09	triangular gold nanoparticles (Tri-Au NPs)	triangular	plasmonics, photocatalysis	158
10	Au nanorods	nanorods	imaging, drug delivery	159
11	Au nanoshells	nanoshells	biomedicine, sensing	160
12	octahedral Au NPs	octahedral	catalysis, environmental applications	161, 162
13	icosahedral gold nanoparticles (Ico-Au NPs)	icosahedral	electronics, sensing, photothermal therapy, drug delivery	163
14	Au nanowires	nanowires	electronics, sensing	164
15	dendritic gold nanoparticles (D-Au NPs)	dendritic	catalysis, biomedical applications	165

confined environment for the controlled formation of Au nanoparticles with uniform size and morphology, making them ideal for applications in catalysis, drug delivery, and sensing.

3.9. Synthesis of Gold Nanoparticles via Photochemical Methods. Au NPs are synthesized photochemically; this is done by the action of light on gold ions in the presence of a stabilizer. The said approach is versatile and nature-friendly, using illumination to prompt gold ions to reduce into metal nanoparticles. This method is known as photochemistry because light energy impinges on a photosensitizer, which, in turn, reduces the gold precursors. The size and shape of the nanoparticles can be easily controlled through parameter tuning such as light intensity, wavelength, and exposure time. In this way, there is a reduction in the use of hazardous chemicals as well as the formation of highly stable and uniform gold nanoparticles, which makes it very promising for applications in various fields, especially in biomedicine, catalysis, and electronics. Sanabria-Calaa et al. have studied the dependence of tetrachloroauric acid concentration, irradiation time, and silver nitrate concentration on the morphology and efficiency of radiation absorption of Au NPs obtained via photochemical methods. The research concluded that the nanoparticle geometry varied with the increase of tetrachloroauric acid concentration, which the decrease in

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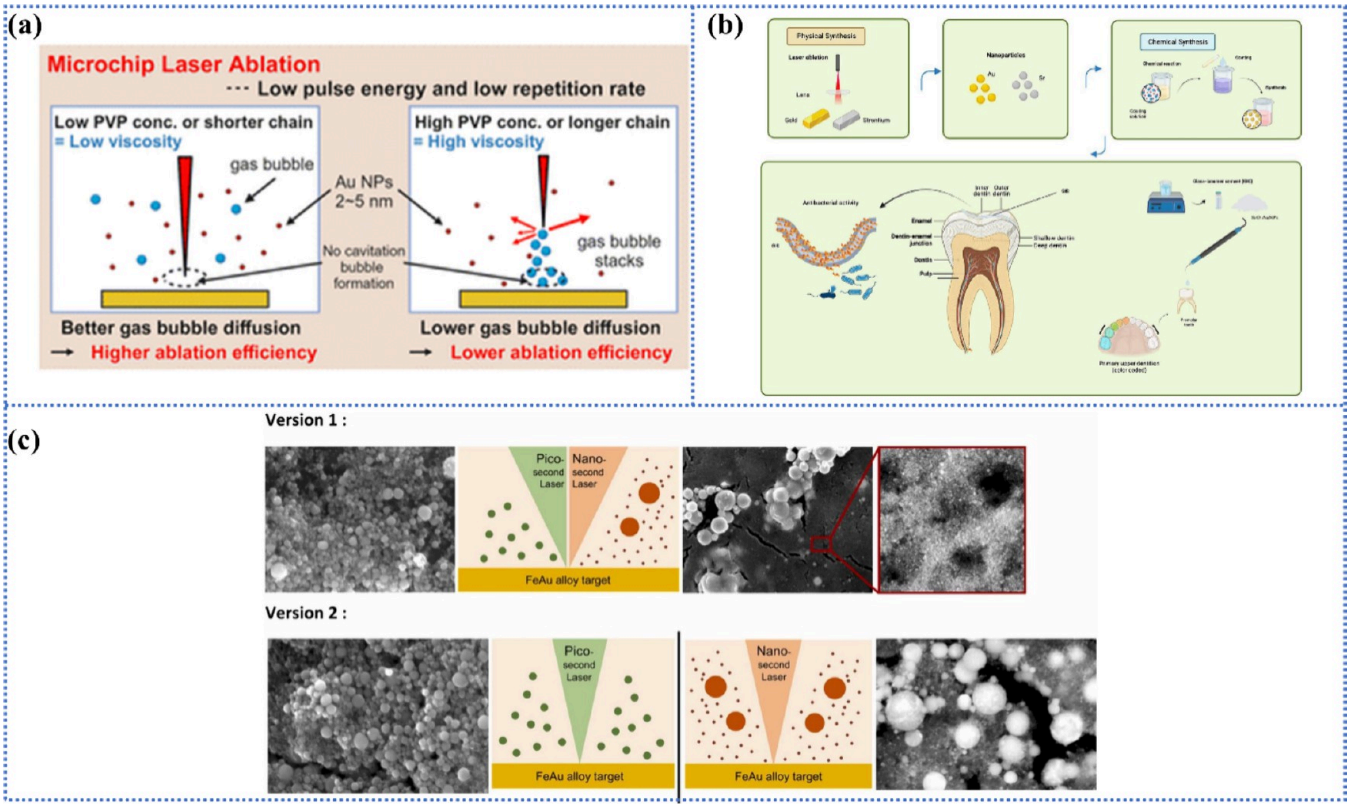

Figure 7. (a) Synthesis of Au NPs in aqueous solution from laser pulses using a microchip laser system is described. [Reproduced with permission from ref 166. Copyright 2024, Royal Society of Chemistry, London.] (b) The showcase is devoted to improving glass ionomer restorations through the use of strontium nanoparticles coated with gold, synthesized using laser ablation in liquid. [Reproduced with permission from ref 167. Copyright 2024, Elsevier.] (c) Iron−gold particles produced by the laser ablation method: Particle properties were based on synthesis parameters. [Reproduced with permission from ref 168. Copyright 2024, Elsevier.]

Table 6. Various Au-Based Nanomaterials Synthesized via Laser Ablation Method

sample	name of material	morphology of material	applications	ref
01	Au/Ag alloy NPs	spherical	biomedical imaging	171
02	Au/Cu alloy NPs	rod-shaped	drug delivery	172
03	Au/SiO	star-shaped	photothermal therapy	173
04	Au/TiO	cubic	catalysis	174
05	Au/Pt	flower-like	biosensors	175
06	Au/Fe	triangular	cancer treatment	176
07	Au/ZnO NPs	hexagonal	anti-microbial activity	177
08	Au/graphene oxide NPs	polygonal	surface-enhanced Raman scattering	178
09	Au/carbon NPs	irregular	environmental monitoring	179
10	Au/polymer composite NPs	prism-shaped	gene delivery	180
11	Au/Si NPs	spherical	photodynamic therapy	181
12	Au/AI NPs	rod-shaped	optical sensors	182
13	Au/CdS NPs	cubic	chemical sensing	183
14	Au/polydopimine NPs	star-shaped	nanoelectronics	184
15	Au/MnO NPs	flower-like	tissue engineering	185

Table 7. Various Au-Based Nanomaterials Synthesized via Microemulsion Method

sample	name of material	morphology of material	applications	ref
01	Au NPs	spherical	catalysis, drug delivery	94, 188
02	Au NPs	rod-shaped	imaging, cancer therapy	189
03	gold nanorods	rod-shaped	photothermal therapy	190
04	Au NPs	cubic	sensors, electronics	191
05	gold nanocages	cagelike	drug delivery, imaging	192
06	gold nanocages	spherical	cancer therapy	193
07	gold nanoshells	core−shell	photothermal therapy	194
08	Au nanostars	star-shaped	imaging, catalysis	195, 196
09	gold nanochains	chain	conductive materials	197
10	gold nanoflowers	flower-like	drug delivery	198
11	gold nanowires	wirelike	electronics, sensing	199
12	gold nanobelts	belt-shaped	flexible electronics	200
13	gold nanoplates	platelike	catalysis, photonics	201

the longitudinal band maximum absorption could support. The continued increase in the irradiation time shifts the position of the longitudinal band to shorter wavelengths, with a decrease in the full width at half maximum (fwhm). Such results open a possible formation and growth mechanism for Au NPs obtained by photochemical synthesis, leading to progress in the understanding of their surface properties and potential applications.[202] Housni and others reported on a simple photochemical process for directly synthesizing BSA-stabilized gold nanoparticles using Irgacure (I-2959) as a photoinitiator. Irradiation with UV light allowed the preparation of protein-stabilized

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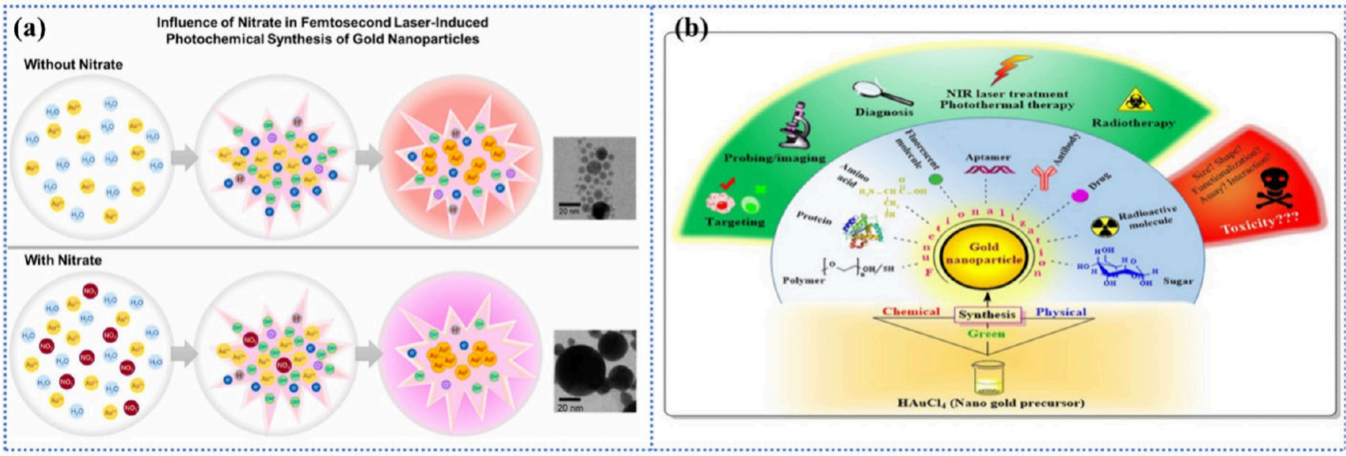

Figure 8. (a) Photochemical synthesis of Au NPs in a nitrate solution using femtosecond laser irradiation. [Reproduced with permission from ref 204. Copyright 2022, Elsevier.] (b) Addressing breast cancer using gold nanoparticles synthesized photochemically: optimizing twinning synthesis and particle engineering for enhanced efficacy. [Reproduced with permission from ref 205. Copyright 2024, Royal Society of Chemistry, London.]

gold nanoparticles without denaturation of the protein in a one-step synthetic process. In addition, they prepared BSA/PEG mixed monolayer-stabilized Au NPs by adjusting the PEG-to-BSA ratio in a one-pot process to examine the effect of the particle size on the size distribution. The results revealed that the photochemical process can produce almost monodisperse mixed-layer stabilized Au NPs effectively.[203] Additionally, Putri et al. studied the effect of nitrate as an electron scavenger in femtosecond laser-based photochemical synthesis of Au NPs. They found that increasing the nitrate concentration enhanced both nucleation and growth rates, leading to larger nanoparticles. In the absence of nitrate, small particles (<7 nm) dominated. Adding small amounts of nitrate increased the fraction of particles in the 7−15 nm range, with a maximum average size of 7.49 nm. Excessive nitrate led to even larger particles that fused together. This work demonstrates the potential of nitrate for controlling the morphology of Au NPs (Figure 8a).[204] Mal et al. discussed the growing role of Au NPs in breast cancer diagnosis and treatment. Despite the effectiveness of traditional therapies, Au NPs stand out, due to their versatile properties, including modifiable shape and size, biocompatibility, and multifunctionality. These nanoparticles offer unique advantages for applications such as photothermal therapy, molecular imaging, and radiotherapy. However, clinical translation of Au NPs is hindered by toxicity concerns in major organs, such as the liver and kidneys. This study explores various design and synthesis techniques to enhance the efficacy, safety, and versatility of Au NPs, aiming to accelerate their clinical use in breast cancer treatment (Figure 8b).[205] Table 8 presents various gold-based nanomaterials synthesized using the photochemical method. This method typically utilizes light irradiation, such as UV or visible light, to drive the reduction of gold salts into nanoparticles, offering precise control over particle size and morphology for applications in catalysis, sensing, and environmental remediation.

3.10. In-Situ Chemical Oxidative Polymerization Method. In-situ chemical oxidative polymerization describes a process where a polymer is formed directly within a reaction mixture via oxidation. During this method, polymer chains are created through chemical reactions with an oxidizing agent, all while the monomer remains in the solution. This eliminates the need for isolating or purifying intermediates, as the polymerization takes place "on-site", within the intended environment.[218−220] For instance, Jayeoye et al., used a green, one-pot chemical oxidative polymerization strategy to fabricate multifunctional Au NPs in a CPs-PAPBA and hydrophilic polymer blend (PVA-HPMC) matrix (Figure 9a). In this process, 3-aminobenzeneboronic acid (ABBA) and gold salt were mixed in an aqueous PVA-HPMC solution, where gold salt reduced to nanoparticles, while ABBA polymerized into its conducting form (PAPBA). The resulting nanocomposite (Au/PAPBA/PVA-HPMC) was applied as a colorimetric probe for cyanide (CN−) detection and for reducing environmental contaminants like Methylene Blue (MB) and 4-nitrophenol (4NP).[221] Furthermore, Jayeoye al. fabricated a gold nanoparticle/polyaniline boronic acid/sodium alginate aqueous nanocomposite ((PABA-SAL)@Au NPs), using an in situ chemical oxidative polymerization method (Figure 9b). In this approach, aniline boronic acid (ABA) reduced gold salt to nanoparticles while also polymerizing into its conducting form (PABA). Sodium alginate (SAL) was used as a stabilizer and solubilizer to enhance PABA's solubility and stability, anchoring the Au NPs. The resulting nanocomposite exhibited antibacterial activity, moderate antioxidant capacity, and good biocompatibility, highlighting its potential for biomedical applications.[222]

Table 8. Various Au-Based Nanomaterials Synthesized via Photochemical Methods

sample	name of material	morphology of material	applications	ref
01	Fe-doped Au NPs	spherical	catalysis	206
02	Ag-doped Au NPs	rod-shaped	biomedicine	207
03	Pd-doped Au NPs	cube	optical properties	208
04	Pt-doped Au NPs	star-shaped	imaging	209
05	Cu-doped Au NPs	flower-like	sensors	210
06	Ni-doped Au NPs	branched	electronics	211
07	Zn-doped Au NPs	icosahedral	optoelectronics	212
08	Al-doped Au NPs	triangular	electronics	213
09	Ga-doped Au NPs	hexagonal	imaging	214
13	Bi-doped Au NPs	dendritic	catalyst	215
18	W-doped Au NPs	bipyramidal	photocatalysis	216
19	Mo-doped Au NPs	rhombohedral	CO_2 reduction	217

4. APPLICATIONS OF GOLD NANOPARTICLES

Au NPs have vast applications in various fields of life. Some of them are discussed below comprehensively (Figure 10).

4.1. Targeted Drug Delivery and Bio Medical Imaging. Au NPs are emerging as powerful tools in biomedical science, especially in targeted drug delivery and imaging.[223] Their unique properties—biocompatibility, ease of functionalization, and ability to penetrate biological barriers—make them ideal for

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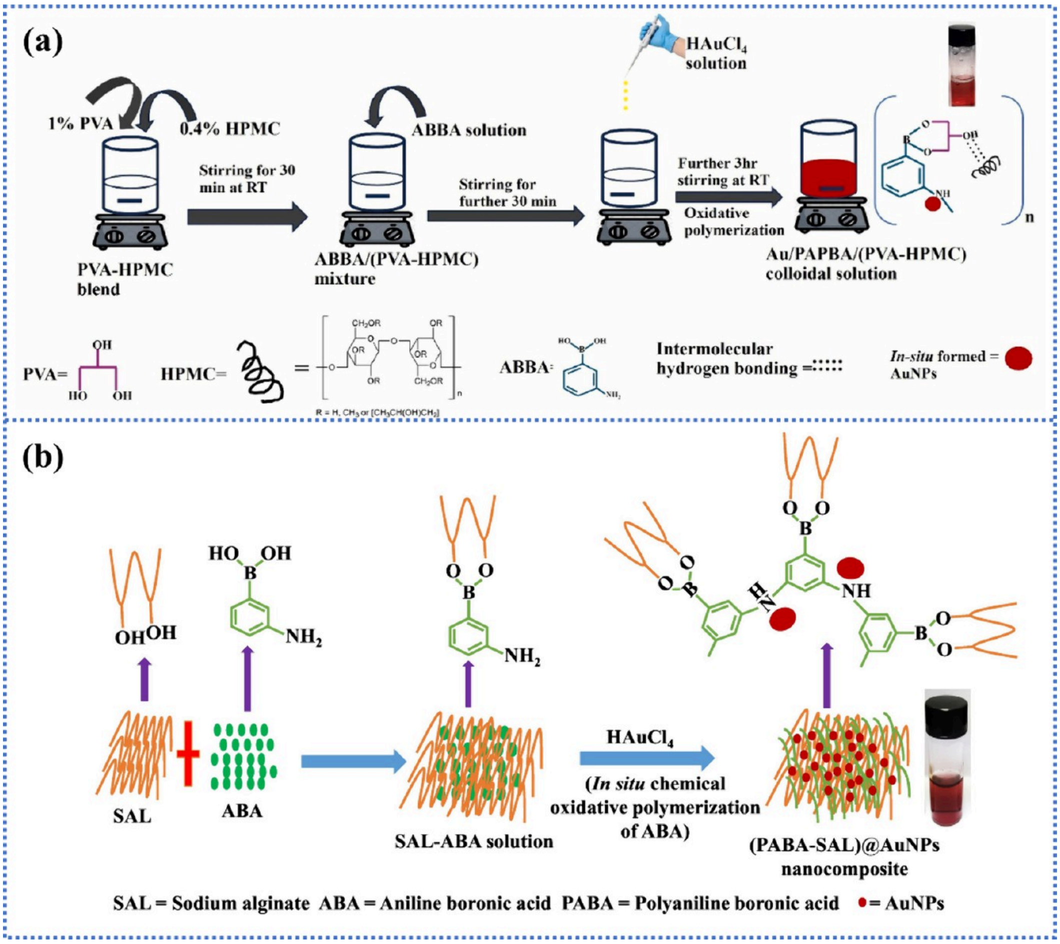

Figure 9. (a) Schematics of Au/PAPBA/PVA-HPMC synthesis at room temperature (RT). [Reproduced with permission from ref 221. Copyright 2024, Elsevier.] (b) Schematic illustration of the synthesis protocol for the (PABA-SAL) @Au NPs nanocomposite. [Reproduced with permission from ref 222. Copyright 2021, Elsevier.]

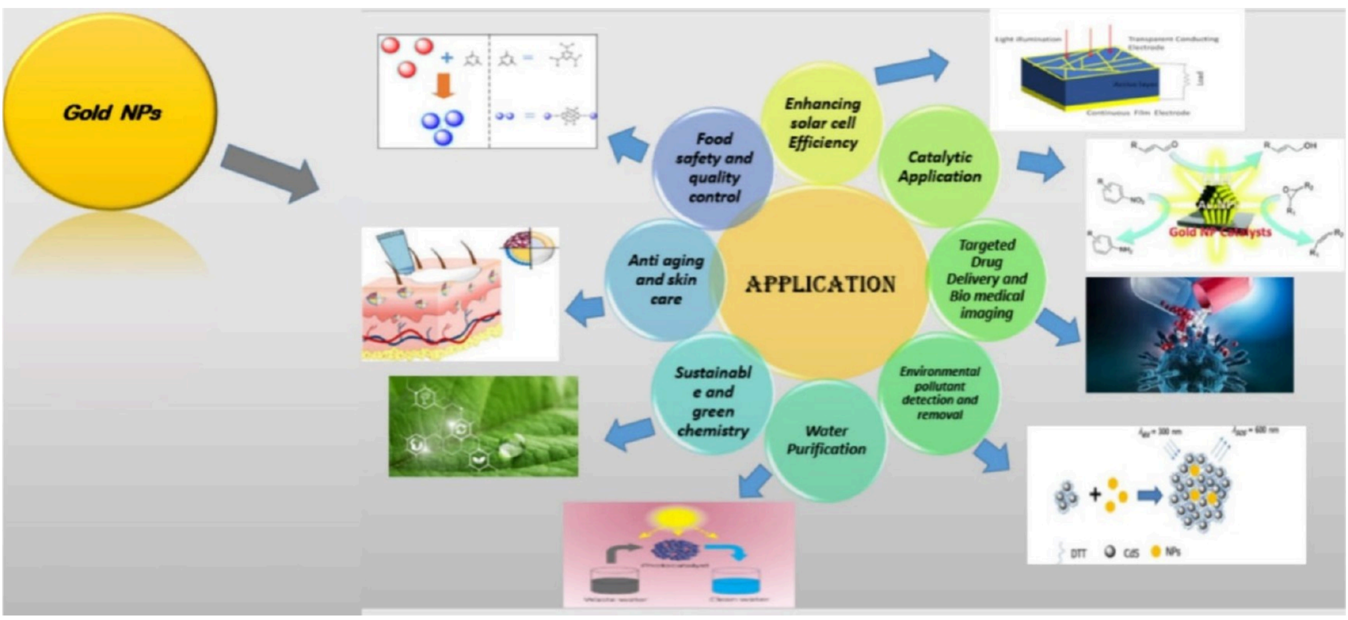

Figure 10. Applications of Au NPs in various fields.

transporting therapeutic agents to specific cells, enhancing treatment precision, and minimizing side effects.[94] In targeted drug delivery, Au NPs can be engineered to carry drugs, proteins, or genetic material, bonding these agents to the nanoparticle surface via covalent or noncovalent interactions.[224,225] Functionalizing Au NPs with specific ligands, such as antibodies or

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Table 9. Biomedical Applications and the Targeted Drug Delivery System Mechanism of Some Gold NPs

sample	name of the material	morphology	synthesis method	role in targeted drug delivery and bioimaging	ref
01	PEG-FA-DTX-Au NPs (functionalized Au NPs)	spherical, slightly larger than Au NPs due to functionalization	chemical reduction with PEG and folic acid functionalization	facilitates targeted delivery of Docetaxel (DTX) to cancer cells; enhances cellular uptake and cytotoxicity specifically in cancer cells, with potential applications in bioimaging and biosensing	245
02	folic acid-coated gold nanoparticles	spherical	coating with folic acid via PEG and FITC	accumulation in cytoplasm of human fibroblasts; no cytotoxicity observed; potential for targeted imaging	246
03	Au-SMCC-DOX nanoconjugates	spherical	doxorubicin conjugation via SMCC linker	overcoming multidrug resistance in hepG2-R cells; enhanced cellular entry, cytotoxicity, and drug retention	246
04	gold nanoparticles	small dimensions	biological and chemical methods (chemical offers better control)	drug delivery systems and bioimaging due to compatibility, tunable stability, and surface properties	247
05	gold nanoparticles (Au NPs)	nanoscale structures	advances in synthetic chemistry for precise control over properties	drug carriers to tumors; biolabeling using single particle detection (e.g., electron microscopy); computed tomography imaging; photothermal microscopy	248
06	AuZE (gold nanoparticles synthesized using ZE)	highly biocompatible nanoparticles	green synthesis using ZE extract	exhibits red fluorescence in the NIR region; enables brain-specific imaging in C57BL6 mice without targeted ligands; applicable for graft transplantation biology and disease diagnosis	249
07	gold nanocomplexes	complex assemblies	combination of gold nanostructures with other biomolecules or agents	enables multimodal detection, photothermal therapy, and ultrasonic diagnostics; improves targeted drug delivery with reduced side effects	250
08	gold nanoparticles (Au NPs)	spherical nanoparticles	trisodium citrate method	serve as the therapeutic agent and imaging marker when loaded into macrophages	251
09	gold nanostars (GNS)	multibranched, star-shaped	green synthesis	exceptional optical properties for bioimaging	102
10	gold nanoparticles (GNP)	spherical, rod-like, or other nanoscale shapes	chemical reduction, seed-mediated growth, or green synthesis methods	serve as contrast agents; leverage surface plasmon resonance for enhanced imaging techniques of biological relevance	252
11	SCx6Au NPs (*p*-sulfonatocalix[6]arene-functionalized gold nanoparticles)	spherical (~7.5 nm size)	synthesized and characterized using UV−vis absorption, transmission electron microscopy (TEM), and surface-enhanced Raman spectroscopy (SERS)	efficient uptake and stimuli-responsive release of doxorubicin (Dox) for targeted drug delivery; facilitates bioimaging using ThT dye as a fluorescent probe	253
12	gold nanoparticles (GNPs)	small, nanoscale size	amenable to various synthesis methods (e.g., chemical reduction, seed-mediated growth)	functionalization allows targeted drug delivery, gene delivery, bioimaging, and diagnostic applications	254
13	gold nanoparticles (Au NPs)	controlled size and shape	improved synthetic techniques	act as carriers for drugs and anticancer agents, used in photothermal therapy, gene therapy, and radiotherapy	255
14	Au NPs/PEI/RhB-HA	nanoparticles	functionalization of gold nanoparticles with hyaluronic acid (HA), stabilized with poly(ether imide) (PEI), and loaded with Rhodamine B (RhB)	targets CD44-overexpressed MCF-7 cancer cells selectively through HA-CD44 receptor binding; enables bioimaging using fluorescence imaging and flow cytometry	256
15	gold nanoparticles (Au NPs)	varies (size, shape, functionalization)	various methods (e.g., chemical reduction, laser ablation, seed-mediated growth)	targeted drug delivery, cancer cell detection, diagnostic imaging, functionalization for specific targeting in prostate cancer therapy and early detection	257
16	gold nanorods	nanorods	synthesized via various methods like seed-mediated growth	bioimaging platform due to strong absorption bands in the near-infrared (NIR) region	258
17	surface-modified Au NPs	nanoparticles	functionalized with polymers, surfactants, ligands, proteins, peptides, or oligonucleotides	enhance specificity and selectivity in drug delivery and bioimaging applications, allowing for targeted therapies and improved imaging contrast	259
18	gold nanoparticles	various shapes and sizes	chemical, physical, or eco-friendly biological methods	targeted delivery systems for anticancer agents, nucleic acids, biological proteins, and vaccines	260
19	curcumin-conjugated gold clusters (CUR-AuNCs)	cluster of ~1−3 nm, uniform size	green synthesis, formed by curcumin reacting with a gold precursor under mild alkali condition	anticancer agent, bioimaging, targeted therapy with less toxicity to COS-7 cells and high toxicity to HeLa cells	261
20	fluorescent gold clusters (FGCs)	nanoclusters (small size, tunable visible emission)	various synthetic approaches (not detailed in the text)	nontoxic alternative to semiconductor nanocrystals, used for stable, bright, and tunable bioimaging, with high biocompatibility and small hydrodynamic size, applicable in in vitro and in vivo imaging	262

Table 10. Catalytic Applications of Some Gold NPs and Their Key Findings

sample	name of the material	morphology	synthesis method	key findings	ref
01	poly-NHC-shell-encapsulated Au NPs	cavity-hosted, dispersed	metal-carbene template approach (MCTA) to synthesize polyimidazolium cages (PICs), used as templates for polyNHC-anchored Au NPs	high thermal, chemical, and pH stability; effective catalytic activity in various reactions; selective nucleation sites for metal deposition; size- and shape-constrained reaction environment	284
02	Au NPs	nanoscale clusters	colloidal routes	catalyze oxidation reactions like CO oxidation	282
03	Au NPs	nanoscale clusters	colloidal routes	catalysts for oxygen activation reactions, such as carbon monoxide oxidation	285
04	anisotropic Au NPs	nanorods, nanostars, nanoflowers, dendritic nanostructures, polyhedral nanoparticles	advanced controlled synthesis methods	catalysis with superior performance (thermal-, electro-, and photocatalysis); control over active sites; optical property tuning (plasmon band)	140
05	Au/TiO_2	clusters (focus on <2 nm)	varies (preparation conditions and pretreatments emphasized)	low-temperature CO oxidation (mechanistic insights discussed)	286
06	CeO_2-supported Au NPs	Au NPs on CeO_2 (crystalline)	deposition on oxide supports	enhanced catalytic performance in carbon−carbon coupling reactions due to Ce^{3+}/Ce^{4+} species	287
07	Au/TiO_2	supported gold on titania	transition-metal oxide support for O_2 activation	CO oxidation and complex reactions like amide synthesis and selective hydrogenation	288
08	composite of nanoscale gold particles and poly(*N*-isopropylacrylamide)	Au NPs embedded within a polymer particle	in situ incorporation under light irradiation	oxidation, reduction, and coupling reactions	289
09	Au NPs (Au)	faceted nanocrystals (average size: 2.2 nm)	immobilized on cationic spherical polyelectrolyte brushes	catalysis: reduction of *p*-nitrophenol (Nip) by sodium borohydride (BH_4^-) in aqueous solution; used in kinetic analysis and temperature dependence studies	290
10	gold-based catalysts	gold nanoparticles (R < 16 nm), homogeneous surface coverage	Au nanoparticles grown on silica beads or plates coated with a titanium oxo-alkoxy monolayer	decomposition of acetaldehyde in plasma-catalytic reactor, selective CO_2 production	291
11	Au NPs	2−4 nm in size, narrow size distribution	reduction of $AuCl_4^-$ using sodium borohydride ($NaBH_4$) on RH-silica-supported Au	catalytic applications, particularly in the reduction of 4-nitrophenol	292
12	gold (Au) catalysts	nanoscale Au particles	typically anchored to oxide supports	hydrogenation of nitroaromatics; catalytic selectivity in hydrogenation processes	293
13	Au NPs	nanoparticles	coprecipitation or deposition-precipitation of $Au(OH)_3$, grafting of organo-gold complexes, mixing of colloidal Au particles, vacuum deposition	deodorizers (Japan), indoor air quality control, pollutant emission control, hydrogen energy carrier production, chemical process innovations	294
14	Au NPs passivated by thiolates	nanoparticles with a monolayer of functional thiolates	modest synthetic effort; self-organization	modeling recognition processes, developing biomimetic catalysts, supramolecular chemistry	295
15	Au NPs/CTS/AC	nanoparticles (Au), chitosan (CTS), activated coke (AC)	green synthesis without additional chemicals, functionalized with CTS	hydrogenation of 4-nitrophenol, hydrogenation of various nitrophenols and azo dyes, environmental pollution treatment	296
16	Schiff-base-stabilized Au NPs	ultrasmall (<5 nm), high dispersion	reduction of hydrogen tetrachloroaurate(III) trihydrate ($HAuCl_4 \cdot 3H_2O$) using Schiff base ligand (1-((E)-(4-(trifluoromethoxy) phenylimino)methyl)naphthalen-2-ol)	catalytic reduction of nitroaromatic compounds (4-nitrophenol (4-NP), 4-nitroaniline (4-NA)), selective sensing of Pb^{2+} ions, antibacterial, antifungal, and antioxidant activities	297
17	Au NPs	highly crystalline, face-centered cubic (fcc) structures	biological and eco-friendly synthesis using SapindusmukorossiGaertn. fruit pericarp (soapnut shells) and $HAuCl_4$ as the precursor	catalytic activity for the chemical reduction of *p*-nitroaniline	298
18	Au NPs	1D, 2D, 3D shapes, hollow, nanoshells	various synthesis methods	plasmon absorption in visible and NIR regions, medical diagnostics, therapy (theranostics)	43
19	Au NPs	nanoparticles (diameter <5 nm)	catalytic synthesis of SWCNTs	synthesis of single-walled carbon nanotubes (SWCNTs)	299
20	Au NPs (Au)	nanoparticles	reduction of Au_2O_3 by molecular hydrogen at elevated temperature and pressure	redox catalysis (conversion of reducing radicals to hydrogen from water in basic solutions)	300

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Table 11. Enhancing Solar Cell Efficiency Applications of Some Au NPs

sample	name of the material	morphology	synthesis method	key findings	ref
01	Au NPs	spherical NPs with varying lateral distributions in PEDOT	Au NPs	spherical NPs with varying lateral distributions in PEDOT	309
02	Au NPs	varied (dependent on size and geometry)	depositing and annealing a gold film on a transparent electrode	enhanced light absorption and power conversion efficiency in organic solar cells by ∼10%	310
03	TiO_2/Au NP/MWCNT	mesoporous film	integrated into photoanodes of DSSCs	power conversion efficiency (PCE) of 6.61%, ∼31% improvement compared to TiO_2-alone cells; stable performance retaining 92% PCE after 10 days	311
04	TiO_2 functionalized with SiO_2/SiDTC	TiO_2 modified with siliceous shells enriched with dithiocarbamate moieties	functionalization with SiO_2/SiDTC	chemical modification with SiDTC improved DSSC performance, enhancing key parameters	312
05	PEDOT:PSS with Au nanoparticles	not explicitly mentioned	incorporation of Au nanoparticles into PEDOT:PSS layers	power conversion efficiency (PCE) improved to 12.85%, an ∼23% enhancement	313
06	silicon (Si) nanoholes (SiNHS)	nanoholes	metal-assisted electroless etching (EE)	SiNHS films were fabricated, showing good compatibility for hybrid solar cells	314
07	Au NPs	incorporated in active layer of PSCs	not specified	LSPR introduced by Au NPs enhances light absorption in the active layer of PSCs	315
08	Au NPs	nanoparticles	dispersed in spiro-OMeTAD HTL solution, positioned during spin-coating	enhanced photovoltaic response in PSCs due to LSPR and electrical effects of Au NPs	316
09	branched gold nanoparticles	branched	solution-based method	successfully grown on glass, silicon wafer, and ITO-coated glass for potential further applications	302
10	ZnO/Si and perovskite/Si	solar cells with gold nanoparticles	Sentaurus TCAD simulation	Fano interference attributed to the sinusoidal relationship between short-circuit current and nanoparticle periodicity	317
11	Au:SnO_2:MgO	Au NP: 30−35 nm	incorporation of Au NPs into SnO_2:MgO	efficiency improved to 4.69% (208% enhancement); increased V_{OC} (725.6 mV) and J_{SC} (9.06 mA cm^{-2}) due to reduced recombination (MgO barrier) and enhanced LSPR effect	318
12	perovskite solar cells (PSCs)	hybrid organic−inorganic	incorporating Au NPs and MgO into mesoporous TiO_2	achieved a power conversion efficiency of 16.1% with high open-circuit voltage (1.09 V) and short-circuit current density (21.76 mA cm^{-2})	319
13	gold nanoparticles	ligand-free, surface plasmon absorption	laser ablation method	gold nanoparticles incorporated into POxT-SH to boost PCE ; increased PCE by 21.4% (to 3.29%) compared to POxT-SH alone in organic solar cells	320
14	hybrid organic−inorganic perovskites	thin film (solar cell layer)	solution processing	perovskites have low optical absorption in the visible spectrum, particularly in the red region (∼600 nm)	321
15	Au NPs	various sizes (48 to 203 nm)	deposition on TiO_2 film	size-dependent light scattering effect	322
16	Au NPs	nanosized particles	not mentioned	NPs induce localized surface plasmonic resonance (LSPR), affecting the near field and interfacial properties of the PSCs	323
17	porous silicon (PSi)	high surface-to-volume ratio, low reflection, high optical gain	metal-assisted chemical etching with varying deposition time (1−7 s) of Ag or Au nanoparticles (NPs)	co-doping of graphene with Au NPs and $(CF_3SO_2)_2NH$ enhances performance	324
18	gold nanoparticles functionalized with fullerene C60 derivative (C60-BCT@Au NPs)	enhances interfacial contact and improves perovskite film crystallinity and morphology	not specified	enhances the interfacial contact at the ETL/perovskite interface; improves charge extraction efficiency and suppresses charge recombination	325
19	TiO_2 blended with Au NPs	characterized by XRD and SEM (morphology not detailed)	hydrothermal synthesis under controlled conditions	TiO_2-Au DSSC performance significantly higher than TiO_2 DSSC	326
20	perovskite ($MAPbI_3$)	thin-film layer	not specified	the absorbing layer integrated with Au nanospheres, achieving higher efficiency through localized surface plasmon resonances (LSPRs) in the range of 300−1100 nm	327

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Table 12. Various Au-Based Nanoparticles and Their Applications in Environmental Pollutant Detection

sample	name of the material	pollutant type	removal method	key outcomes	ref
01	Au NPs	nitrobenzene (NB)	electrochemical detection using DPV on modified electrode	high sensitivity (1.01 $\mu A\ \mu M^{-1}\ cm^{-2}$), low detection limit (0.016 μM), selective and efficient detection of NB, with good recovery in real water samples, using green synthesis method	341
02	gold (Au) nanostructures	toxic pollutants (e.g., heavy metals, small molecules, proteins, nucleic acids, antigens)	electrochemical sensing and environmental remediation	effective detection and removal of trace amounts of toxic pollutants by tuning size, shape, morphology, and composition	342
03	HA−Au NP (humic acid−gold nanoparticles)	organic pollutants (e.g., in soil)	in-situ fabrication of HA−Au NP in presence of target pollutant	enables direct detection of organic pollutants; wide pH range (2−12) for fabrication; weak background SERS spectra of HA; allows ultrasensitive chemical analysis	343
04	Au NPs	heavy metals/cationic metal ions, toxins, pesticides	colorimetric detection	high sensitivity and selectivity, low toxicity, high stability, facile processability, unique optical properties	344
05	Au NPs@BSA/AGM	Hg^{2+} and Pb^{2+}	removal: agarose gel membrane trapping Au NPs@BSA for pollutant removal	practical nanocomposite material for pollutant extraction from aqueous solutions	345
06	Au NPs-BI (biphenyl-4,4′-dithiol-functionalized gold nanoparticles)	total gaseous mercury (TGM)	adsorption onto quartz fibers	high Hg adsorption capability at subppb levels; effective for defined (~4.5 ng/m^3) and environmental (~1.5 ng/m^3) concentrations; robust procedure with CVAFS detection	346
07	Au NPs-based sensors	heavy metals (mercury)	microfluidic sensors with digital camera	detection limit of 0.6 $\mu g\ L^{-1}$ achieved for mercury	347
08	graphene/Au-NPs	organic dyes	adsorption and degradation via •OH radical generation	synergetic adsorption and degradation enable efficient dye removal; high catalytic efficiency due to substrate proximity to active sites; prevents Au-NP aggregation	348
09	gold−carbon nanocomposites	chemical contaminants	detection, degradation, removal	high sensitivity, broad selectivity, desired stability, minimal sample handling for pollutant analysis and removal	349
10	biosynthesized gold and silver nanoparticles	various pollutants	green synthesis methods; optical sensors for detection	sustainable, eco-friendly synthesis; unique SPR absorbance in visible spectrum allows easy detection	350
11	colloidal Au NPs	Hg(II) (mercury)	scanning and sequestration of Hg(II) using Au NPs as a catalyst, with sodium citrate as a reducing agent	efficient removal of Hg (II) from aqueous solutions even in the presence of other cations (Cu(II), Fe(III)), formation of amalgams, morphological transformation, hydrophobicity aiding recovery, interaction studied using UV-vis, ICP-MS, (S) TEM, SEM, EDX, and XRD	351
12	PDA-g-C_3N_4/Au	nitroaromatics	reduction by $NaBH_4$	highly efficient catalytic reduction of nitroaromatics with a rate constant of 0.0514 s^{-1} and TOF of 545.60 h^{-1} for 4-NP	352
13	Streptavidin−biotinylated DNA probes modified gold nanoparticle	mercury (Hg(II))	lateral flow biosensor for Hg(II) detection	detection limit: 2.53 nM	353
14	ZnO-Au nanocomposites (ZnO-Au NCs)	polychlorinated biphenyls (PCBs) and its isomers	surface-enhanced Raman scattering (SERS) and photocatalytic degradation	high selectivity for detection and removal of PCBs and isomers; SERS detected tetrachlorobiphenyl isomers at low concentration (6 mM); high photocatalytic activity under UV irradiation to degrade pollutants; apparent rate constant of catalytic reaction: 0.021/min; effective in both detection and degradation of organic pollutants	354
15	Au NPs	cationic (Rhodamine B, Methylene Blue), anionic (Congo Red, Methyl Orange)	catalytic reduction using sodium borohydride	particle size: <24 nm (electron microscopy); effective degradation of cationic and anionic dyes: 87% (RhB), 97% (MB), 92% (CR), 95% (MO)	355

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Table 13. Water Purification of Various Au-Based Nanoparticles and Their Key Outcomes

sample	name of the material	target containments	removal method	key outcomes	ref
01	PDA-*g*-C_3N_4/Au (green synthesized Au catalyst)	nitroaromatics (e.g., 4-NP, 2-NP, 2,4-DNP, MO, CR, EBT)	catalytic reduction using $NaBH_4$	high catalytic activity with rate constant of 0.0514 s^{-1}, stable over ten cycles, effective across various nitroaromatics, eco-friendly	352
02	Au NPs	metal ions, organic compounds	detection and elimination of pollutants through green synthesis methods	Au NPs are efficient for water depollution due to their enhanced optical and catalytic properties; they offer fast, easy, and cost-effective green synthesis methods and have vast applicability; they are seen as a promising solution for future water depollution	359
03	Au/TiO2 (Gold nanoparticles supported on titanium dioxide)	organic pollutants (e.g., dyes)	solar-driven photocatalysis	Au/MO plasmonic photocatalysts are effective for water purification	360
04	rGO−Au NP membrane	Rhodamine B (RhB)	vacuum filtration	Au NPs on rGO surface (size: 8−10 nm, lattice spacing: 0.0241 nm, cubic lattice of gold)	361
05	FeO/Au NPs (iron−gold core−shell nanoparticles)	Aniline Blue (AB) dye	biodegradation	maximum dye degradation at 70 °C and pH 10; antimicrobial activity against various microorganisms; biocompatible up to 500 μg/mL; recyclable	362
06	PDA-*g*-C_3N_4/Au	nitroaromatics	reduction by $NaBH_4$	PDA served as a reductant and stabilizer, avoiding secondary contamination.	352
07	nanogold-bioconjugate (NGBC)	organophosphorus pesticides, microbial pathogens (gram-negative and gram-positive bacteria, yeasts)	adsorption of pesticides and antimicrobial action	NGBC adsorbs different organophosphorus pesticides; high antimicrobial activity against bacteria and yeasts; causes rupture of microbial cell membranes; successfully purifies water from pathogens and pesticides in a single operation	363
08	noble metals (Ag, Cu)	chemical and microbiological pollutants	photocatalysis and plasmonic heating	noble metals enhance the antimicrobial effects through a combination of dark antimicrobial properties and photo disinfection via reactive oxygen species and plasmonic heating	364
09	Au NPs	bacteria (gram-positive and gram-negative pathogens)	antibacterial activity	good antibacterial activity against waterborne pathogens, indicating potential use in water purification.	365
10	gold nanoparticle supported on alumina	inorganic mercury	adsorption (batch and column studies)	adsorption capacity for mercury is 4.065 g per g of Au NPs; the alloying chemistry of Au aids in mercury sequestration from drinking water	366
11	PVA:GA:Au hydrogel (AC) nanocomposite	freshwater shortage (desalination)	solar steam generation	light absorption increased with Au NPs (74%)	367
12	Au NPs@c-silica hybrid	seawater, wastewater	solar thermal conversion for water purification	achieves solar thermal conversion efficiency of 94.6% with minimal Au usage (25 $\mu g\ cm^{-2}$)	368
13	Au NP/PDMS Nanocomposites	aromatic solvents, sulfur-containing contaminants	thermal treatment	effective for removing aromatic solvents and sulfur-containing contaminants from water.	369
14	Au NPs	water pollutants	water purification (filter paper)	demonstrated applications in water purification	370
15	Au NPs (nanogold)	heavy metals, fertilizers, detergents, pesticides	nanotechnology-based water treatment	enhanced catalytic activity, visible surface plasmon resonance color changes, and chemical stability make nanogold effective in water treatment	106
16	Au NP-loaded PAN, GO-PAN, rGO-PAN	organic dyes	photothermal heating and catalytic decomposition	Au NPs-loaded membranes exhibit faster removal of dyes than GO-PAN and rGO-PAN due to catalytic decomposition	371
17	Au NPs	metal ions, organic compounds	detection and elimination of pollutants through green synthesis methods	Au NPs are efficient for water depollution due to their enhanced optical and catalytic properties; they offer fast, easy, and cost-effective green synthesis methods and have vast applicability; they are seen as a promising solution for future water depollution	359
18	Au/TiO_2 (gold nanoparticles supported on titanium dioxide)	organic pollutants (e.g., dyes)	solar-driven photocatalysis	Au/MO plasmonic photocatalysts are effective for water purification	360
19	rGO−Au NP membrane	Rhodamine B (RhB)	vacuum filtration	Au NPs on rGO surface (size: 8−10 nm, lattice spacing: 0.0241 nm, cubic lattice of gold)	361
20	FeO/Au NPs (iron−gold core−shell nanoparticles)	Aniline Blue (AB) dye	biodegradation	maximum dye degradation at 70 °C and pH 10; antimicrobial activity against various microorganisms; biocompatible up to 500 μg/mL; recyclable	362

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Table 14. Food Safety and Quality Control Applications of Various Au NPs

sample	name of the material	target analyte	detection method	advantages	ref
01	Au NPs	foodborne pathogens	lateral flow assay (LFA)	quick detection, portability	385
02	gold nanoparticles (Au NP)	contaminants, pesticides, heavy metals, adulterants, and other contaminants	nanosensing, nanobiosensing	aggregation, fluorescence quenching, broad absorption at surface plasmon band, biocompatibility, effective in detecting contaminants, biocompatibility for food safety.	386
03	functionalized Au NPs (with Raman molecules)	contaminants and allergens	surface-enhanced Raman scattering (SERS)	high sensitivity, enabling detection with altered interparticle distance for enhanced signal	383
04	Au NPs	hazardous chemicals (pesticide residues, heavy metals, banned additives, biotoxins)	colorimetric sensing	simple, quick, sensitive, good biological affinity, narrow size distribution	175
05	Au NPs	food contaminants, disease biomarkers, pathogens	LSPR, colorimetry, FRET, SERS	simple preparation, high surface-to-volume ratio, excellent biocompatibility, unique optical properties	387
06	nanosensors	foodborne pathogens, contaminants, and intoxicants	selective binding with biological components and detection via suitable transducers	fast, sensitive, portable detection; ensures prompt preventive action in food safety enhancement	388
07	Au NPs	biomolecules, environmental toxins, drugs	biosensing (based on localized surface plasmon resonance and functionalization)	size-dependent optical properties	389
08	Au NPs	bacteria and their toxins in food (e.g., milk, meat)	colorimetric detection based on localized surface plasmon resonance	low-cost, easy-to-perform, rapid point-of-need measurements, suitable for food safety applications	380
09	Au NPs	food contaminants	colorimetric sensing	easy preparation, rapid detection, high sensitivity, and naked-eye sensing	391
10	alginate-Au NPs THI	thermal history (temperature and duration)	localized surface plasmon resonance (LSPR) of gold nanoparticles	convenient and reliable	390
11	gold nanoparticles (GNPs)	illegal food additives	colorimetric and electrochemical sensors	high selectivity and sensitivity	392
12	Au-NP-modified tungsten oxide (WO_3) nanoflakes	nitric oxide (NO)	amperometric techniques	high sensitivity (~39.37 μA cm^{-2} mM−1), wide linear range (~10 μM to 5.78 mM), low detection limit (~0.12 μM), fast response (1.7 s), high selectivity, stable (only 7.54% current decrease after 31 days), suitable for environmental and food applications	393
13	Au-NP-based thermal history indicator (THI)	temperature history	UV−vis spectrophotometry	simple visual color change, sensitive to both storage time and temperature, proactive monitoring of product quality, suitable for safeguarding high-value biological products (e.g., enzymes, antibodies, plasma, stem cells)	394
14	colloidal Au NPs	Enterobacteriaceae family members	lateral flow immunoassay (LFIA)	simple, rapid, easy synthesis, visual detection, stability, commonly used in food and water safety	395
15	Au NPs	metal ions, small biomolecules, enzymes, antigens, antibodies	biochemical assays, sensors	suitable for various biochemical applications (environmental monitoring, medical diagnostics)	396
16	gold nanoparticles (GNPs)	*Escherichia coli* O157:H7	photothermal effect-based immunofiltration strip	sensitive, rapid, simple, hand-held, low-cost	397
17	Au NPs	histamine	aptamer-based assay with salt-induced aggregation of Au NPs (indicated by color change from red to blue)	rapid, sensitive, reproducible, low detection limit (8 nM ~0.05 mg/kg), suitable for on-site use, good correlation with HPLC and ELISA results	398
18	electroanalytical nanostructured sensor (Au NPs and rGO)	Vitamin C	electroanalytical sensing using screen-printed carbon electrodes modified with Au nanoparticles and reduced graphene oxide	low cost; easy sample preparation; fast response; high reproducibility	399
19	Au NMs (gold nanomaterials)	biomolecules (for imaging and therapy)	computed tomography (CT), X-ray imaging, surface-enhanced Raman spectroscopy (SERS) imaging	high spatial and density resolution, reliable imaging modes for biomedical applications, useful for drug delivery and diagnostics	400
20	Au NPs-*Staphylococcus aureus* monoclonal antibody conjugates	*Staphylococcus aureus*	immunochromatographic test strip using a double-antibody sandwich format	simple, fast, low-cost; high sensitivity and specificity; rapid results (within 10 min); detection limit: 103 CFU/mL; detection rate: 98.7%; suitable for food safety and clinical diagnosis	401

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Table 15. Application of Various Au-Based Nanocomposites in Antiaging and Skincare Products

sample	name of the material	morphology	key findings	ref
01	Au NPs with PVP stabilizer	spherical and irregular	Au NPs with PVP stabilizer are present as individually dispersed nanoparticles and as groups of physically separated primary nanoparticles in both freeze-dried form and cosmetic cream; no major modifications in primary sizes, morphology, and functional properties within the cream medium; surface charge differences were observed in cream, but stability remained comparable; further studies are recommended to assess Au NPs' behavior over typical cream usage timespan	412
02	Au NPs	3–5 nm	Au NPs significantly attenuated AGE-induced RAGE protein expression in fibroblasts	413
03	Au NPs	varying charge, shape, and functionality	nanoparticle penetration into different skin layers assessed qualitatively and quantitatively	414
04	gold nanoparticles (OP-Au NPs)	average particle size: 45.42 nm, surface plasmon resonance (SPR) at 535 nm	synthesized using aqueous extract of dried onion peels (OP) as a green method; strong antibacterial and anticandidal activity antioxidant and proteasome inhibitory potential	415
05	Au NPs	spherical, synthesized via ultrasonic spray pyrolysis (USP)	improvements in collagen quality between 18% and 24% in standard cream with Au NPs; hydration of skin (stratum corneum) increased by 6.4%–9.6% in standard creams with Au NPs	416
06	Au NPs in 3HFWC-W matrix	spherical, combined with patented 3HFWC-W matrix	collagen quality improvement of 45.7% in cream with 3HFWC-W and Au NPs combination	416
07	gold nanoparticle-incorporated collagen sponge (CS-Au)	collagen sponge with Au NPs incorporated	enhanced stability against enzymatic degradation; increased tensile strength; better hydrolytic degradation compared to CS	417
08	P. ginseng leaves-capped Au NPs (PgAu NPs)	not explicitly mentioned	PgAu NPs have multifunctional properties for cosmetic applications; effective in scavenging radical cations; possess moisture retention properties	418
09	*Hubertia ambavilla*-mediated gold nanoparticles	nanoparticles (synthesized using a green process)	free-radical scavenging potential and antioxidant properties; protect against damage to fibroblasts and dermal cells caused by ultraviolet A radiation	419
10	snail slime-based gold nanoparticles	hybrid gold nanoparticles, 14 ± 6 nm wide, inorganic metallic core decorated by snail slime components	showed antioxidant and tyrosinase inhibition activity (DPPH, ABTS, and tyrosinase assays)	420
11	Au NPs (synthesized with sodium citrate, AuCit)	spherical (suggested by DLS, SEM, TEM)	UV-vis absorption showed wavelengths of 520–525 nm	421
12	Au NPs	spherical (observed by TEM)	modified with sulfadiazine (SDZ) for Hg^{2+} detection; aggregation of Au NPs causes color change from red to blue-gray with increasing Hg^{2+} concentration; anti-interference properties	422
13	gold nanorods (GNRs)	nanorods	strong plasmon absorption in the IR-A wavelength range (700–1400 nm), effective for blocking IR-A radiation	423
14	Au NPs	nanosized (1–6 nm)	able to penetrate deeper layers of rat and human skin (epidermis and dermis)	424
15	GA–Au NPs (gallic acid-coated gold nanoparticles)	spherical, approximately 40 nm in diameter (TEM and DLS analysis)	inhibit high glucose-mediated MMP-1-elicited type I collagen degradation in dermal fibroblast cells	425

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Table 16. Various Gold Nanoparticles Applications in Sustainable and Green Chemistry

sample	name of the material	morphology	application area	key findings	ref
01	Au NPs synthesized using tea leaves in aqueous media	typically, spherical with a variable nanosize distribution depending on conditions	educational demonstrations in green chemistry and nanotechnology	synthesis of Au NPs using green reagents (tea leaves) and water, eliminating toxic chemicals, surfactants, and capping agents; the process is economical, efficient, and suitable for introductory laboratory curricula; supports teaching green chemistry principles and sparking discussions on sustainability in chemistry education	433
02	Au NPs	nanoscale, spherical, polydisperse	biosensing, environmental monitoring (Pb^{2+} detection), material science	synthesized using *Moringa oleifera* bark broth without surfactants or templates	434
03	Au NPs	not specified	nanotechnology, environmental, industrial	controlled biosynthesis of gold NPs by fungal microorganisms	435
04	Au NPs	not specified	nanotechnology, industry, medicine	evaluated using green chemistry metrics; solvent usage is a significant challenge, typically resulting in high PMI	436
05	Au NPs	not specified (likely spherical or varied)	diagnostics, imaging, structural design, antimicrobial applications	green synthesis is a promising and eco-friendly method using plant extracts; the process is simple, cost-effective, and nontoxic; secondary metabolites like phenols, alkaloids, and proteins act as reducing and capping agents in nanoparticle synthesis; these nanoparticles exhibit antimicrobial potential	437
06	Au NPs	nanoparticles	biocompatible materials, colloidal suspensions	green synthesis using aqueous media and environmental-friendly reducing agents, with *Egregia sp.* algae extract providing biomolecules for shell formation; the extract serves both as a reducing agent and stabilizing capping shell, aiding biocompatibility and achieving narrow size distribution	438
07	Au−peptide−alginate biohydrogel	Au NPs <25 nm in diameter, peptides on surfaces	biomedical (antimicrobial, catalytic activity), Industrial	rapid synthesis using antimicrobial peptides as reducing agents; high stability with alginate as a stabilizing agent; effective catalytic activity in reducing 4-nitrophenol and hexacyanoferrate(III); antimicrobial activity against pathogenic bacteria; eco-friendly, robust, and potentially scalable for industrial and biomedical use	439
08	GNPs-Trys-GNCs nanocomposite	gold nanoparticles (GNPs) with an average diameter of 5.5 nm and gold nanoclusters (GNCs) about 1 nm, embedded in trypsin molecules	heavy-metal ion sensing and elimination	GNPs-Trys-GNCs are synthesized via trypsin as reducing and linking agent.	440
09	Au NPs	characterized by XRD, FTIR, FESEM, and EDS	nanotechnology, medicine, electronics, catalysis	synthesized via two methods: wet chemical (using sodium citrate) and green chemistry (using *Vigna radiata*)	441
10	Au NPs	nanoparticles (size and shape may vary)	cancer therapy (cytotoxicity)	promising cytotoxicity; activates apoptosis, necrosis, and autophagy in cancer cells	442
11	Au NPs	not specified	biomedical and technological	green synthesis approaches offer sustainable alternatives, reducing the environmental impact while also affecting the biocompatibility and potential biomedical applications	443
12	gold (Au)	nanoparticles (NPs, <5 nm)	green and selective catalytic processes	Au-based catalysts show high activity for small molecule activation (CO, O_2, H_2, H_2O) under mild conditions	444
13	bimetallic gold (Au)−palladium (Pd) nanoparticles (NPs)	core/shell configuration (Au core, Pd shell)	catalysis (oxidation of benzyl alcohol)	Pd(II) ions are reduced by *E. coli* cells with H_2 to form Pd(0), which accelerates Au(III) reduction; comparable catalytic activity to chemical counterparts for oxidation of benzyl alcohol at 90 °C	445
14	Au NPs	various forms: single gold atom NPs, alloyed Au NPs, core−shell Au NPs	catalysis, antifungal action, antibacterial activities, sensors, etc.	Au NPs are synthesized using plant-derived molecules due to advantages in shape/size control and nontoxicity; synthesis methods and characterization vary based on reducing agents	446
15	plant-based Au NPs	nanoscale, synthesized using plant extracts (e.g., *Medicago sativa*, OlaxScandens, *H. ambavilla*, *H. lanceolatum*)	cancer detection, treatment of solid tumors, drug delivery	biocompatible and nontoxic synthesis; used for detection and treatment of cancer; fluorescent markers for cancer detection; reduced cytotoxicity with plant-based synthesis	447
16	Au NPs	typically, 1−100 nm in size	various industries, including technology, medicine, and environmental sector	versatile applications in innovative technologies	448
17	Au NPs	uniform, 5 nm in diameter	catalysis (conversion of *p*-nitrophenol to *p*-aminophenol)	synthesized using a low-energy gold sputtering method and biofriendly deep eutectic solvent (DES); simple, economical, ecofriendly, and rapid synthesis; high reproducibility; successfully used in catalytic reaction, with in-situ UV-vis spectra recorded during the process	449
18	Au NPs	nanoscale, spherical (typically)	biology (labeling, heating, sensing, delivering)	can be synthesized biologically using bioentities like bacteria, yeast, fungi, plant, fruit extract, peptides; biosynthesis is more biocompatible and environmentally friendly; offers more sustainable, nontoxic synthesis methods under mild conditions (ambient temperature/pressure); historically used for therapeutic and decorative purposes; potential for use in various biological applications	450
19	gold nanoparticles (GNPs)	roughly spherical	catalysis (reduction of 4-nitrophenol)	synthesized using *Aspergillus trinidadensis* fungi as reducing and capping agent without solvent interference	451

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Table 16. continued

sample	name of the material	morphology	application area	key findings	ref
20	Au NPs	nanosized gold particles (various shapes depending on synthesis)	therapeutic applications, including targeted drug delivery, cancer treatment, gene therapy, antimicrobial agents, biosensors, imaging	Au NPs are synthesized using biomolecules as reducing and stabilizing agents; they are eco-friendly, nontoxic, cost-effective, and have unique physicochemical properties; they have potential in a variety of biomedical applications	452

peptides, allows them to bind selectively to targeted cells. This targeted approach is especially valuable in cancer treatment, where Au NPs can recognize markers specific to cancer cells, delivering chemotherapeutic drugs directly to tumors and sparing healthy tissue.[226] The Enhanced Permeation and Retention (EPR) effect further supports this application, enabling Au NPs to accumulate in tumors with leaky vasculature and facilitating passive targeting. Active targeting, achieved by combining EPR with functionalization, can further boost specificity.[227] Despite these benefits, Au NP-based drug delivery systems face challenges in clinical application, including toxicity, biodistribution issues, and regulatory barriers.[228] Researchers are thus focused on optimizing particle size, shape, and surface chemistry to improve biocompatibility and address these limitations.[229] As the technology advances, Au NPs have the potential for changing therapies and being useful in cancers and diseases where local therapy is crucial. Besides drug delivery, Au NPs have a large number of benefits for imaging.[230] Their optical characteristics, including surface plasmon resonance (SPR), are important in dark-field and multiphoton microscopy, where they help to improve the visibility of cells and their structures. Gold is a high-atomic-number element, which is why Au NPs can be good contrast agents in the computed tomography (CT) with higher X-ray absorption than iodine-based agents.[231] This makes it easier in soft tissue and tumor imaging, where Au NPs can either be passively or actively incorporated and accumulate.[232] Optoacoustic imaging that uses light and ultrasound also receives advantages from Au NPs. Ultrasonic imaging is attained when laser light exposed on Au NPs transforms the light to heat; this, in turn, expands and produces the ultrasonic waves necessary for imaging.[233] Such applications demonstrate the specific capabilities of Au NPs for versatile usage within diagnostics and therapy, thereby highlighting their significance for changing outlooks on the management of diseases caused by various pathogenic factors.[234] Biofunctionalized gold nanoparticles are becoming versatile tools in biomedical imaging due to their tunable properties and superior imaging performances. Its application covers four types of imaging including computed tomography, magnetic resonance imaging, fluorescence, and surface-enhanced Raman scattering (SERS), where each technique takes advantages of physical and chemical property of Au NPs to provide high resolution, deeper tissue penetration, and specific imaging without damaging the tissues.[235] By presenting an increased resolution, Au NPs are capable of imaging tissues with greater depth and therefore enhance the efficacy of tumor identification, drug delivery, and visualization of vascular systems. Since it can remain deposited in certain regions, either by simple diffusion or active targeting, it can be used to perform imaging of regions of interest such as tumor microenvironments.[236] This deep tissue imaging capability is invaluable, especially in cancer, where early and accurate identification greatly enhances the treatment results. Although Au NPs themselves do not exhibit magnetic properties, they can be conjugated with magnetic NPs like iron oxide to obtain core–shell NPs appropriate for magnetic resonance imaging (MRI).[237] Choosing gold as a high-contrast material and iron oxide for its ability to attach to enzymes within the body, the composite particle makes for an ideal contrast medium for tumor imaging as well as tracing cells.[238] Thus, the functionalization of Au NPs with fluorescent dyes or quantum dots makes them suitable for use in fluorescence imaging. Upon activation by a specific wavelength of light, the fluorophores emit a measurable signal that allows for extended imaging and

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monitoring cellular and molecular activities.[239] Another advantage of Au NPs is resistance to photobleaching of fluorophores since fluorophores have a limited lifespan, using Au NPs lengthens this lifespan and increases fluorescence. This property is beneficial for many cases, where objects have to be imaged for a long time, or when trajectory tracking is needed at the cellular level, to see how cells react to the treatments over time.[240] Another unique feature of Au NPs is the phenomenon of SERS, which is surface-enhanced Raman scattering of signals at the Au NP surface. This property makes it possible to detect biomolecules in very low concentration and also helps to obtain high-resolution images on cell surfaces, cancer biomarkers, and other molecular targets. SERS allows for monitoring at the very small signal level, which is important for cancer diagnostics and for defining biomarkers that indicate the onset of a disease.[241] Au NPs exhibit versatility in numerous imaging methods, such as CT, MRI, fluorescence, and SERS imaging modes. In this case, functionalizing of the Au NPs with targeting molecules such as antibodies or aptamers makes it possible for these nanoparticles to attach to definite cells or tissues, adding to the specificity and accuracy of the imaging. In CT imaging, gold has a high atomic number and, hence, provides high contrast for the visualization of soft tissues and tumors.[242] Thanks to the properties of SERS and fluorescence, Au NPs are rather important in early-stage disease diagnosis, the monitoring of cellular processes, and drug delivery processes. Due to the strong optical properties and high potential contrast of Au NPs, as well as the opportunity for functionalization, they are optimal for the development of further noninvasive imaging procedures.[243] Au NPs are especially useful for characterization and point-of-care monitoring and could revolutionize biomedical imaging, because they offer imaging agents that are safer, more sensitive, and specific. In the future, as new Au NPs are developed through further research, more potential uses will be discover and untapped of Au NPs in diagnostic imaging and therapeutic monitoring.[244] Table 9 outlines the biomedical applications and targeted drug delivery system mechanisms of various Au NPs. Gold nanoparticles are extensively used in medical diagnostics, imaging, and therapeutic applications due to their biocompatibility, ease of functionalization, and ability to target specific cells or tissues, enhancing drug delivery efficiency and reducing side effects.

4.2. Catalytic Applications of Gold Nanoparticles in Chemical Reactions. Au NPs have emerged as one of the most efficient catalysts for numerous chemical reactions, inclusive of those occurring in industries as well as those that appear to be environmentally friendly.[263] In contrast to bulk gold, which is relatively unreactive, Au NPs possess considerable catalytic properties on the nanoscopic level attributable to enhanced surface-area-to-volume and electronic effects inherent to nanoscale systems.[264] This catalytic effectiveness, coupled with stability and ease in functionalization, renders Au NPs for rightful application in environmental remedial measures and differential oxidation reactions, particularly in sustainable chemical reactions. Among the most distinguished uses of Au NPs lies in the catalytic sequential process of conversion of carbon monoxide (CO) to carbon dioxide (CO_2). Originally, this reaction needed high temperatures and potentially dangerous, toxic metal catalysts, which create environmental and health problems. Different from this, Au NPs are capable of catalyzing this reaction at much lower temperatures, giving better yields, less byproducts formation, and greater energy efficiency.[94] Catalytic tests show that Au NPs within the size range of 2−5 nm supported on metal oxide like TiO_2, CeO_2, and Fe_2O_3 exhibit higher catalytic activity. This increased activity is due to the enhancing effect that Au NPs has on the support material, which enhances the activation of the reactants at a lower energy.[265] This property makes Au NPs especially suitable for uses in pollutant mitigation technologies such as catalytic convertors in automobile exhaust systems where CO emissions must be minimized. Au NPs also display high catalytic activity in selective oxidation reactions that are crucial in industries involving the generation of high-margin goods, such as pharmaceuticals and fragrances. For example, Au NPs promote the selective oxidation of benzyl alcohol to benzaldehyde, which plays a crucial role in producing diverse drugs and aromatic organics.[266] In comparison with conventional catalysts, Au NPs possess higher selectivity, and in many cases, there is no need to use severe reaction conditions and/or other reagents. Thus, the performance of Au NPs in selective oxidation can be timed by adjusting the size and shape of the particle, which determines the number of active sites on nanoparticles, and by choosing the appropriate support materials, which can improve the stability of catalytic activity.[267] It has been found that the pliability of Au NPs in catalysis is highly attributed to the catalyst surface properties that can be altered to enhance a particular reaction. Trying to change the particle size, it is possible to influence the number of active sites because, for the samples with small particles, the relative number of reactive sites is higher. The morphology also affects the catalytic properties; for example, rod or tetrahedron structures can increase the catalytic activity for some reaction pathways with larger numbers of more-active crystallographic facets.[268] Also, the organic ligands may be attached to the surface of the Au NP or co-catalysts deposited on the Au NP surface enhance the selectivity or the rate of the reaction to meet specific industrial application specifications.[269] Au NPs are further used in green chemistry principles, in which the least amount of waste generation and energy consumption is focused. Since they perform reactions under mild conditions and offer less toxic byproducts than highly toxic products of other chemical reactions, they can be used in green chemistry.[270] For instance, in water treatment, Au NPs can facilitate the degradation of organic contaminants, and, in chemical production, they can prevent the formation of dangerous waste, due to higher selectivity and efficiency of the reactions being achieved.[271] This makes them reusable and stable for more applications, thus cutting their frequency of requiring replacement and reducing their operational costs. Au NPs are quickly revolutionizing the arena of catalysis through their interesting physicochemical attributes, as well as flexibility. They offer potential for fundamental and transformative innovation in both traditional and newly developing fields of industrial chemistry, environmental cleaning, and green production. As more studies are conducted around the size, shape, and materials for supporting them, Au NPs can become a foundation of modern catalysis that will contribute to making chemical processes greener, safer, and more efficient in different areas. Au NPs are regarded promising in various areas, including catalysis, due to their high selectivity as well as minimal environmental impact in comparison to other conventional catalysts used in the industry. They are able to promote a wide range of chemical transformations, including hydrogenation, cross coupling, as well as photocatalysis, at moderate temperature and pressures, which makes the overall cost and impact of the process much lower.[272] The addition of hydrogen to unsaturated molecules (hydrogenation) is an essential reaction in numerous industries, including petrochemicals and food. Conventional hydrogenation catalysts such as

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platinum and palladium may prove efficient but are expensive and have the tendency to degrade quickly. Altogether, current research demonstrates that, specifically as a part of the heterogeneous catalytic system with metals such as palladium or platinum, Au NPs are effective in hydrogenation reactions like alkynes-to-alkenes and alkenes-to-alkane transformations with the same order of efficiency.[273] These Au NP alloys decrease the use of costly metals, while showing better stability and resistance to deactivation at the same time. Due to their selectivity and efficiency, these complexes could be valuable for practical implementation of hydrogenation reactions, which consume fewer resources and provide fewer byproducts.[274] Au NPs have also become important catalysts in cross-couplings, critical to the synthesis of complex organic structures applied in drugs and polymers. Classic cross-coupling reactions, including Suzuki, Sonogashira, and Heck couplings, have been previously strongly associated with palladium catalysis. Mounted somewhat for Au NPs, it is now starting to be shown that these reagents are capable of affecting these bond-forming transformations under significantly milder conditions, often in aqueous media. We believe that this approach not only minimizes the negative effect on the environment but also ensures superior and more reachable conditions for the reaction's scalability. The efficiency of Au NPs in the cross-coupling reactions demonstrates their potential and the possibility of new CO-independent catalysis, which seems to lower cost and lessen dependence on dangerous metals in synthetic organic chemistry.[275] There are outstanding questions and concerns, such as the use of Au NPs to perform photocatalytic reduction reactions. This paper shows that Au NPs have superior photocatalytic characteristics, because the incident light locates highly localized electric fields, also known as hot spots. Such plasmonic effects increase the photocatalytic rates of a reaction through the photocatalytic generation of high-energy electron−hole pairs and localized surface heating to bring about reactions that would otherwise require very high temperatures. Similar to most applications of Au-NP-based photocatalysts, the environmental application of these materials also involves the degradation of organic pollutants in water that promises to be a way to purify water.[276] Au NPs are also being considered for their application to decomposing water to give hydrogen and oxygen, which is key in clean hydrogen fuel fabrication.[277] Interestingly, the photocatalytic Au NPs can work under visible light; thus, there is no requirement for the UV sources and the reaction overall can be much more efficient. Au NPs are providing revolutionary green and economical catalytic applications at different areas of the industries including hydrogenation, degradation of pollutant agents, etc. Catalytic properties, stability, and activity under mild conditions make them an essential tool of modern catalytic chemistries. By enhancing their nanostructure through alloying, functionalization, and size increase or decrease, Au NPs may be used as a replacement or additive to conventional catalysts in many settings to align with safer, more-effective scientific processes.[278]

Au NPs are rapidly emerging as superb candidates among all heterogeneous catalysts especially for reduction reactions, which forms the hub of chemical, pharmaceutical, and agriculture sectors. Due to high catalytic efficiency, the possibility of recyclability, and the applicability of reaction mild conditions, Au NPs are used in the known processes in which the energy supply and maximum reduction of byproducts are a priority.[6] Reduction reactions, including nitroarene reduction to amines, are essential in developing intermediate and active components in many products. Usually, these reactions are performed under severe conditions and result in high yields of waste; however, with Au NPs, this is not the case. A literature review indicates that Au NPs are capable of facilitating reduction reactions at ambient temperatures and the rate of byproducts formed is also low, thus conforming to the principles of green chemistry.[279] Au NPs' own catalytic activity can be further improved by alloying them with metals such as palladium or platinum or by anchoring them on carbon or silica substrates. Such supports cement the nanoparticles, keep them from caking and retain their catalytic activity across several cycles of reactions making Au NPs a cost-effective technology improvement for industrial processes.[280] Green chemistry aims at reducing the negative effects of chemical processes, and Au NPs contribute in this area by virtue of their high selectivity, comparatively low operating temperatures, and reusability. As such, they are able to selectively change the substrates without using up a lot of resources, enhancing efficiency. In reactions such as selective oxidation of alcohols, reduction of nitro compounds, and hydrogenation, the Au NPs have also been shown to work under green chemistry conditions. A second advantage relates to waste minimization, in that Au NPs can be reused multiple times as catalysts without significant decrease in efficacy due to their recoverability from reaction media.[162] In addition, the chemical activity of Au NPs can be controlled by varying particle size, shape, and support material. Small Au NPs, particularly those with diameters less than 5 nm, have been reported to have enhanced catalytic properties, because of their larger surface-area-to-volume ratio and the enhanced number of active sites. The shape of the particles is also very important; for instance, longitudinal or triangular Au NPs present more reactive planes, which can favor some reactions. Furthermore, the type of support material selected for the nanoparticles, such as TiO_2, SiO_2 or CeO_2, act not only as a stabilizer but also affects the dispersion and reactivity of the nanoparticles. For example, the addition of TiO_2 can facilitate the electron transfer reactions, thus improving the general efficiency of the Au NPs as redox catalysts.[281] The fact that the catalytic activity of the Au NPs can be tuned selectively for different reactions makes them handy in industry. It is, therefore, evident that the stability, reusability, and ability of Au NPs to conform to green chemical processes point toward their ability to displace more risky or less effective promoter catalysts where sustainable and inexpensive green chemistry techniques are called for. Depending on the change in the properties of the particles and the materials that support them, Au NPs can be used in any number of catalytic ways to produce drugs, for example, or to lessen the amount of waste created by industries. Gold nanoparticles are one of the most promising materials for application in sustainable catalysis as it provides more efficient and environmentally friendly ways for necessary chemical conversions.[282] Their applicability to reduction reactions and compliance with the principles in green chemistry make them ideal for the modern, sustainable industry. Ongoing research that focuses on additional aspects of size, shape, and nature of the support materials may further improve the Au NPs performance and broaden the scope of the application of the renewable and cost-efficient catalytic processes.[283] Table 10 summarizes the catalytic applications of various Au NPs and their key findings. Au NPs have been found to exhibit significant catalytic activity in a range of reactions, including oxidation, reduction, and CO_2 conversion, thanks to their high surface area, tunable size, and ease of functionalization, making them ideal candidates for use in green chemistry and sustainable processes.

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4.3. Role of Gold Nanoparticles in Enhancing Solar-Cell Efficiency. Recent advancements in functional materials such as Au NPs are applied in the solar-cell technology due to its unique optical and electronic property which enhances the efficiency of the solar cell. Thus, Au NPs provide a significant contribution to improve absorption of light, effective charge transport, and heat-resistant material for photovoltaic applications.[17] Another significant feature of Au NPs is their LSPR which means that certain spots on the Au NPs absorb light waves at specific wavelengths to intensively absorb and scatter light energy. This effect increases the amount of light that actually reaches the active layer of the cell; it, in particular, helps thin-film and organic solar cells; the latter type of solar cell often suffers from low light absorption rates, because of their thickness. The scattering from Au NPs aid in the manipulation of and confining of the light within the active layer of the cell, thus increasing the light to electricity conversion efficiency. It is not only the efficiency of utilizing light provided to the cell augment but also the possibility of more photon engaged with active material to form electron−hole pairs and thus augment the photocurrent.[301] In addition to light absorption, Au NPs enhance charge transport in solar cells by generating local electric fields that help in the extraction of photogenerated electron hole pairs, thus decreasing their recombination time. These systems reduce the recombination losses, which is an important factor enhancing charge collection efficiency, which is useful in high-performance solar cells. One of the biggest benefits of Au NPs is that they significantly increase charge separation and transport capabilities particularly with stand-alone metal and organic/perovskite based cells, which known to have high recombination rates.[302] Au NPs also expand the solar spectral range of amorphous silicon solar cells to the near-infrared domain. This spectral broadening is useful because a range of conventional solar-cell materials absorb light poorly, primarily within the visible range. Integrating Au NPs enhances the ability of the cells to absorb and scatter the photons from both the visible light and the near-infrared region, resulting in a higher efficiency of power conversion. This expanded spectral response is necessary for the next generation solar cells that are designed to capture maximum sunlight.[303] In the current world, perovskite solar cells which are generally inexpensive and efficient have also showed great improvement when conjugated with Au NPs, which, therefore, show great potential in boosting the development of solar cells.[304] The enhancement of light absorption by Au NPs in the course of designing perovskite solar cells also contributes to the stability of the perovskite layer, which is usually vulnerable to variations in environmental conditions. Incumbent of Au NPs within the perovskite layer improves the light catchment, thus improving the power conversion efficiency. However, Au NPs increase the layers' chemical stability of the perovskite layer and improve the cells' durability to moisture, temperature variations, and other conditions that usually affect perovskite solar cells.[305] Au NPs also decrease the reflective losses, which are a significant parameter in the case of the solar cell. Reflective loss arises when incident light is reflected off the cell surface, and this type of loss tends to lower the efficiency. Au NPs decrease the surface reflectance and confine incoming light in the more interior sections of the cell structure. This light-trapping function can reduce the reflectance losses by as much as 30%, and thus increase the energy conversion capability of the cells.[306] Apart from optical enhancement, the Au NPs work for the thermal stability of the solar cells, although the cells that are made from organic and perovskite materials are known to be degraded under longer exposure of light and higher temperatures. As a heat dissipation structure, Au NPs assist in distributing heat in the cell in a systematic manner. Another thermal management property emerging from this study underlines how cells with Au NP integration do not overheat when illuminated with simulated sun light and how this prevents thermal degradation and maintains high efficiency for longer time. Due to great thermal conductance of Au NPs, the lifetime of cells in operation is prolonged by the adequate heat dispersion.[307] Au NPs essentially can be implemented in all types of solar cells: silicon, organic, dye-sensitized, and perovskite solar cells. That is why Au NPs are suitable for the development of solar technology for a wide range of applications, starting from conventional PV systems and ending with the possibilities of solar technology. Since they are highly versatile, they can be incorporated into various cell structures, setting a foundation for Au NPs in the development of renewable energy systems.[308] Table 11 outlines the enhancing solar-cell efficiency applications of various Au NPs. The table includes the material's morphology, synthesis method, and key findings, showing how different shapes, sizes, and surface modifications of Au NPs contribute to the improvement of solar-cell performance, particularly by enhancing light absorption, charge separation, and overall energy conversion efficiency.

4.4. Gold Nanoparticles in Environmental Pollutant Detection and Removal. Au NPs provide a variety of ways to identify pollution effects in the environment. Au NPs have significant SPR characteristics that cause a visible color transformation when it conforms with pollutants of interest.[25] From this property, colorimetric sensors have been developed for fast, inexpensive, and visual-based detection of pollutants. Heavy-metal ions, such as mercury (Hg^{2+}) or lead (Pb^{2+}), cause the aggregation of Au NPs, which then causes a color change that can be easily observed visually or by using low-cost and basic spectroscopic methods.[328] At the same time, Au NPs facilitate the electron transfer between the pollutant and the analyzed elements in the electrochemical sensor. Au NPs were employed on the electrode surfaces by researchers to develop sensors with high sensitivity and selectivity to certain pollutants.[329] Au NPs allow for the enhancement of pesticides and organic pollutants such as polychlorinated biphenyls (PCBs), and the sensitivity is all improved by the increase of electrode transfer properties and surface plasmon resonance (SPR) properties.[330] For this reason, Au NPs are applicable in the surface-enhanced Raman scattering (SERS), a technique that helps to amplify the Raman scattering signals of adsorbed molecules. This enhancement enables the identification of minimal levels of polluting compounds that have lower concentrations. SERS-based sensors with Au NPs can measure organic pollutants such as PAHs at trace levels that are significantly lower than reported detection limits.[331]

Au NPs, when functionalized, can turn off the fluorescence of some dyes and molecules in the presence of pollutants. Some researchers have conjugated fluorescent markers to Au NPs and that provided the basis for sensors that detect pollutants, depending with change in fluorescence intensity.[332] Industrial pollutants like nitroaromatics present in industrial waste can be easily quantified by the fluorescence quenching mechanism at traces.[333] Most importantly, Au NPs are immeasurable for the removal of pollutants through various methods. Au NPs have features that allow them to reduce large molecules of pollutants into harmless substances. They are effective mostly to degrade organic compounds like dyes and pesticides in water and

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contaminated soil.[334] Au NPs help to degrade dyes such as Methylene Blue, which are used frequently in textile industries, into harmless products. Their catalytic efficiency can be further improved by using material like titanium dioxide (TiO_2) or zinc oxide (ZnO), which creates a composite material.[335] Au NPs when modified with appropriate ligands can selectively adsorb heavy metals, including arsenic (As), cadmium (Cd), and lead (Pb) from water sources and therefore are useful in the purification of drinking water. The Au NPs are functionalized with thiol or amine groups and therefore have the ability to selectively capture heavy-metal ions from various water sources marked by contamination. This approach is particularly valuable in regions where pollutants from industrial activities such as heavy metals are dominant.[336] Au NPs improve the photocatalytic characteristics of some materials, thus promoting pollutant degradation on exposure to light. When mixed with semiconductors like TiO_2, they are capable of breaking down hard insoluble pollutants dissolved in water and wastes in the air. While in the view of sunlight, the Au NPs supported on TiO_2 can degrade pesticides, which makes this a sustainable solution for the management of agricultural runoff.[337] The Au NPs have a virusidal character that can help neutralize microbes associated with the pollutants. In water treatment, they are employed to filter out pathogens and thus assist in increasing water that is safe for drinking. Au NPs interact with bacterial and fungal cell walls of pathogens present in wastewater and halt the progression of disease-carrying pathogens for use in other applications. Pollutant removal efficiency of recyclable nanomaterials is a function of particle size, shape, charge, and modification.[338] The Review draws and talks of several areas where these parameters are optimized for improved performance. Nanoparticles have a higher surface area/volume ratio, making them more reactive, and certain shape geometries increase the SPR effect, which are favorable for detection and catalysis (rods, cubes). Specific pollutants are selectively adsorbed with functional groups like thiols, carboxyls, or amines which are grafted on the Au NP surfaces. Au NPs are usually anchored onto solid support systems such as activated carbon, silica, or polymeric resins to enhance stability and allow for reuse in abstraction processes.[339] The prospects of using Au NPs in pollutant sensing and elimination processes has its drawbacks: first, the expensive costs of synthesizing Au NPs and second, the overall challenge of synthesizing large quantities of Au NPs for large-scale environmental purposes.[340] Au NPs are generally well tolerated without evident systemic toxicity; however, the chronic ecotoxicological effects of these NPs are not yet fully understood because NPs themselves have the potential to accumulate in ecosystems and living organisms. To ensure the sustainability of application of these Au NPs, more efforts are channeled toward synthesizing Au NPs that can be easily recovered and recycled in subsequent reactions. The future work is therefore set on the fabrication of inexpensive, eco-friendly Au NPs and new composites that can work around existing challenges. It also contributes to increasing the sensitivity and selectivity of Au-NP-based sensors and developing the possibility of their application to an extensive range of pollutants. Table 12 summarizes the applications of various Au NPs in environmental pollutant detection and removal. The table includes the pollutant type, removal method, and key outcomes, highlighting how Au NPs, through their unique surface properties and functionalization, effectively target and remove heavy metals, organic dyes, and other hazardous pollutants from water and air, offering promising solutions for environmental remediation and monitoring.

4.5. Applications of Gold Nanoparticles in Water Purification. Gold nanoparticles (Au NPs) are known to be used in water purification based on their ability to observe, adsorb, and reduce water pollutants. In addition Au NPs are superior in their catalytic degradation ability specifically for the contaminated structures like dyes and pesticides; sample detection of trace pollutants like heavy metals or pesticides the Au NPs generate visible or electrochemical signs that suggest presence of contaminants at very low concentrations.[24] These nanoparticles facilitate the breakdown of dangerous substances into less hazardous or nonhazardous elements in industrial and agricultural wastewater to make them useful. Consequently, Au NPs are also efficient in removing heavy metals when the thiols are added to it to have a connection with the metals like lead, cadmium, as well as mercury. This application is particularly important in regions with industrial or mining activities.[356] For decontamination, Au NPs possess antibacterial features that counter ad hoc pathogenic microorganisms in water while neutralizing bacteria, viruses, and fungi without the use of toxic chemicals. This function plays a crucial role in protecting the quality of drinking water and treated wastewater.[357] In combination with semiconductors, Au NPs exhibit an augmentation of photocatalytic reactions. because of its ability to break down pollutant under the sunlight, this sustainable process harness solar energy thereby being eco-friendly and energy efficient for water purification, mainly in areas of limited access to technology and electricity.[358] Table 13 highlights the use of gold-based nanoparticles (Au NPs) for water purification, detailing the types of target contaminants, the methods employed for their removal, and the key outcomes. It demonstrates how Au NPs, with their unique properties, are employed in removing pollutants like heavy metals, organic compounds, and pathogens, showcasing their effectiveness in enhancing water quality with sustainable and efficient methods.

4.6. Gold Nanoparticles in Food Safety and Quality Control. Au NPs are outstanding and versatile tools for food safety and quality control, because of factors such as high surface-to-volume ratio and easy functionalization, optical properties, and stability. These characteristics make Au NPs highly suitable as pathogen and toxin, food contaminants, and spoilage indexes biosensors. In several areas, Au NPs are uniquely important to food safety and quality assurance.[372]

Bacterial pathogens are of significant concern in the food industry, because they have the potential for provoking serious health complications. Au NPs are potential candidates for rapid and sensitive detection techniques of these pathogens. Au NPs are applied in colorimetric methods that undergo a color variation when in contact with particular pathogens or toxin. This interaction causes clustering or declustering of the Au NPs resulting in a discernible color change. Several of colorimetric sensors have been implemented for the detection of *E. coli*, salmonella, listeria, and other foodborne pathogens.[373] Au NPs are also used in lateral flow assays (LFA), same as pregnancy strips, for pathogen and contaminant discovery in foods. These assays are easy, use a few pieces of apparatus, and are sensitive to very low concentration of pathogens. For instance, LFA strips containing Au NPs have been designed for *E. coli* O157 detection in food, thereby displaying potential for onsite food safety analysis.[374] Some of the chemical contaminants include pesticides, heavy metals, and mycotoxins that are potential threats to food safety. These contaminants are detected by using

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Au NPs in different techniques at very low concentrations. The Au NPs have a factor of high surface area and plasmonic attribute which amplify the Raman signals, hence making the technique of SERS very sensitive and able to detect even traces of contaminants. Enhanced by the Au NP-based SERS, it is possible efficiently detect various hazardous substances, including pesticides as malathion or carbendazim, heavy metals as mercury and lead, and other toxins.[375] Au NP-modified electrodes are also used in the required electrochemical sensors for the detection of toxins and contaminants in food samples. These sensors are sensitive, have repeatable measurements, and can detect contaminants at low concentrations, which is critically important in regulations of food safety.[376] Au NPs are also used for detecting spoilage biomarkers, which allows one to implement control over the release of unsuitable products to the market.[377] Decomposition in food products is known to liberate volatile organic compounds (VOC) as metabolic intermediates. By incorporating certain receptors onto the surface of Au NPs, these receptors can detect VOCs emitted in connection to the freshness of food, in real time.[378] For example, ammonia, a sign of meat spoilage, has been detected by sensors made of Au NPs. Besides, Au NPs can be embedded into various packaging materials as spoiling sensors with colorimetric response. Discoveries in the constituent product consistencies may include changes in pH or temperature that alter the nanoparticle-embedded packaging that yields a visible alteration in color where such a packing denotes spoiled food.[379] Apart from safety, Au NPs are utilized in qualitative evaluation to ascertain that the food meets specific required standards before reaching the end consumer. They are employed in the following measures to assess the quality of both the ingredients and the end products. Au NPs can be engineered to target quality nutrients necessary in common foods and food supplements such as vitamins and minerals.[380] For instance, biosensors formed from Au NP have been designed to quantify glucose and cholesterol in progilateral, to uphold standard quality of diary.[381] Au NPs also work well in the determination of adulteration, which is infamous in luxury food products like honey, olive oil, and spices. For instance, Au NP-based assays is applied to detect the added particular sugars in honey or to confirm the genuineness of olive oil through examination of its chemical profile.[382]

However, there are several benefits associated with the application of Au NPs in the food safety area. Au NPs have high sensitivity and specificity; it enables the identification of very low levels of pathogens, toxins, and contaminants in foods and, hence, safety from foodborne pathogen. Also, the Au NP-based sensors and assays can be further developed for fast analysis methods; this feature allows continuous monitoring and tests at the site. Most of the Au NP-based sensors developed are inexpensive and easily reproducible; thus, they can be useful in large-scale food safety analysis.[383] However, there is a limitation to the use of Au NPs as food safety markers. The problem with Au-NP-based assays is that they may not be stable or give reproducible results when applied to different matrices of food samples.[384] Barriers within the realm of the existing regulatory approval processes can also pose a threat to the broad application of Au NP technologies. In addition, although Au NPs are regarded as biocompatible, their material effects and potential health hazards have not been fully investigated in the environment and products. Table 14 presents the application of Au NPs in food safety and quality control, listing the target analytes, detection methods, and key advantages. It highlights the versatility of Au NPs in detecting contaminants, pathogens, or adulterants in food products, offering benefits like high sensitivity, rapid detection, and nontoxic properties, making them an ideal solution for ensuring food safety and quality.

4.7. Gold Nanoparticles in Anti-Aging and Skincare Products. Au NPs have attracted a considerable amount of interest in the skincare and cosmetic industry because of their nanosize, large surface area, ability to be functionalized, and biocompatibility.[402] Such properties make Au NPs useful in antiaging and skincare formulations ranging from function as a carrier of the active ingredients to skin rejuvenation attributable to antioxidant and anti-inflammatory properties. Gold nanoparticles can be defined as particles having a size range of 1−100 nm and a high surface area to volume ratio that can enable them to come into contact with cell structures.[403] The properties of Au NPs that make it advantageous for use in skincare products include the following: the capability of Au NPs of crossing the skin barrier, the stratum corneum, to deliver a higher concentration of active ingredients; the chemical stability of the Au NPs, since gold does not oxidize, thus improving the stability of the formulation; and the biocompatibility of the Au NPs eliminating any inflammation and rash, therefore it can be used on all skin types. They include chemical reduction methods, in which gold salts are reduced with agents such as citrate; green synthesis that uses plant extracts such as tea leaves or aloe vera as reducing agents; and seed mediated growth which provides a better particle size and shape control.[404] Depending on chosen synthesis method, the stability, size distribution, and surface properties of the produced Au NPs affecting the safety and effectiveness of using them in cosmetics are variable.[405] The obtained Au NPs possess multiple antiaging activity mechanisms, including antioxidant, anti-inflammatory, as well as photoprotective ones. With regard to function, Au NPs are involved in the neutralization of free radicals in a way that they prevent oxidative stress that enhances skin aging. Free radicals resulting from the effects of UV light and pollution damage collagen and elastin, leading to wrinkles and tightness. These molecules can be neutralized by Au NPs and prevent skin cells damage which otherwise leads to skin aging.[406] Moreover, Au NPs can also promote fibroblast to synthesize collagen, a protein that gives skin firmness and elasticity to make it look young with few lines and wrinkles.[407] They also have anti-inflammatory properties to which also soothes for clients with sensitive skin or skins that are prone to easily get rosacea, etc.[408] Moreover, the Au NPs can improve skin barrier protection against UV rays that are the cause of early signs of aged skin. Despite the fact that Au NPs themselves do not possess sun screening properties but can be conjugated with UV filter agents for increased photoprotective effect. One of the major uses of Au NPs in skin care products is that they can be used as a delivery system for the various active constituents. Because of the size and surface available for modification, active compounds can be delivered deeper into the skin layers, hence enhancing the bioavailability of these ingredients. Au NPs can also incorporate peptides, vitamins, or other anti-aging molecules, which are tethered onto the Au NPs, allowing them to penetrate deeper layers of the skin and release their activity at a slower rate. Such a slow release is especially beneficial for products containing retinol and Vitamin C because such compounds are unstable in most products. Au NPs, when incorporated with moisturizing agents like hyaluronic acid, increase the penetration of such molecules into the skin layers, enhancing the skin's ability to retain moisture, and diminishing the looks of fine lines.[409] Following

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the success in laboratories, golden beauty appeared in serums, creams, and face masks. It can be actively included in antiaging serums and creams, as well as to create an immediate effect on the skin (for example, skin brightness and smoothness) and a long-term one, such as collagen production. They are also used in brightening masks, which give "instant" skin tightening and brightening for whitening the skin tone and enhancing the luminosity; in eye creams, where the Au NPs contribute anti inflammation, collagen stimulation, and reduction of puffiness and circle around eyes since Au NPs penetrate through the skin layers and accumulate in the dermis layer,[410] and, although Au NPs have numerous positive impacts, the issues of nanoparticle penetration and build up in the skin. To date, studies regarding the use of Au NPs in topical applications have not fully determined the effects of nanoparticles. However, the FDA and the European Commission have provided guidelines for the use of nanoparticles in the cosmetic industry.[411] Many research studies show that Au NPs have cytocompatibility and fairly intrinsically bland at moderate concentrations. But one must always pay attention to or consider the particle size, shape, and concentration in formulations, because they play an important role in biocompatibility. Furthermore, while many products that incorporate nanoparticles are required to state this fact (N. Chompoopong, Skin Phenomena in Patients Using Nanogold Products, Table 1), the main skin complaints reported by patients using nanogold products include the following: itching, skin dryness (154 of 173, 88.2%), skin redness (69 of 173, 40.0%), and oiliness (98 of 173, 56.6%). Hybrid nanoparticles involve the incorporation of other materials, including silver or zinc oxide, into Au NPs for wider uses; controlled release systems, which involve altering the surface of Au NPs to offer a series of active ingredients over time to further enhance the firm's antiaging products. In the future, formulations may consist of a set of Au NPs adapted for different skin types or skin diseases, getting optimal therapeutic effect without considerable side effects. Formulations with Au NPs can be regarded as a promising perspective for antiaging and skin care products, used not only as active agents but also for targeted delivery systems. Due to their ability to exhibit anti-inflammatory, antioxidant, and collation promotional characteristics, they are ideal in use for luxury and niche skincare products preparation. However, it must be understood that it features, by definition, an emerging technology and only its constant refinement in conjunction with the formulation of clinically proven schedules of application can substantiate both the effectiveness in the treatment of certain diseases and rigidity of potential side effects on the long run, with regard to the general population.Table 15 summarizes the application of gold-based nanocomposites in antiaging and skincare products, including their morphology and key findings. It demonstrates how these nanocomposites, with their unique surface properties, contribute to enhanced skin penetration, anti-inflammatory effects, and improved skin regeneration, making them promising candidates for use in cosmetics and skincare formulations.

4.8. Gold Nanoparticles in Sustainable and Green Chemistry. Au NPs are essential in green and sustainable chemistry because they possess a high active surface-area-to-volume ratio, photocatalytic activity, and biocompatibility.[82] They are employed in many such processes as catalysts, renewable energy systems, and pollutant sensing element. Au NPs are especially useful in applications for the reduction of pollutants in catalytic processes. They are capable of promoting diverse chemical transformations under reasonably mild conditions thereby reducing energy costs and emissions of hazardous byproducts.[426] Some potential uses of catalysis with reference to Au NPs concern carbon monoxide oxidation where Au NPs are particularly suitable for the oxidation of this gas to carbon dioxide at ambient temperatures to improve exhaust fumes and gas wastes from automobiles and industries.[427] Au NPs are also employed in the chemo selective oxidation of alcohols into aldehydes or ketones without formation of any toxic compound. This reaction is widely used in the synthesis of pharmaceutical and fine chemicals and in view of the green chemistry principles, reported methods generate minimum waste and do not require a hazardous reagent.[266] Furthermore, Au NPs are used to catalyze hydrogenation reactions that are typically performed under strenuous and non-aqueous conditions. In the synthesis of various reduced compounds in the food and pharmaceutical industries, they help make production less toxic. This makes Au NPs environmentally friendly and suitable for environmental monitoring and pollutant detection due to their optical and electrochemical properties, which allow for greater sensitivity at lower concentrations.[428] Their utilization in this area helps protect the environment by aiding in the tracking of pollutants in water, soil, and air. Some examples include inorganic bench Au NPs functionalized with selective ligands or biomolecules, which can selectively interact with toxic metals such as mercury and arsenic. The presence of these metals incurs alterations on the surface plasmon resonance (SPR) property of the Au NPs, with a common effect being the color change which form the basis of a rapid analytical method for detection of pollutants within contaminated water bodies.[429] Aptamer or antibody functionalized Au NPs are introduced into the sensors for pesticide detection. This application makes promise of fostering the production of food safely in a sustainable manner because pesticide residues in water can now be monitored in real time to prevent water pollution.[430] In gas sensors, Au NPs improve the selectivity of the gas sensors to volatile organic compounds (VOCs) and other polluting agents. These sensors are applied for the assessment of air quality in urbanized territories, industrial regions, and limited areas. The large surface-area-to-volume ratio of Au NPs gives a better detection rate and makes them particularly suitable in dilute pollutant concentrations.[431] Au NPs are also useful in sustainable energy by increasing the performance of renewable energy systems and environmental treatment processes. Au NPs enhance the photoelectrochemical features pertinent to photovoltaic cells, including dye-sensitized solar cells (DSSCs).[311] Therefore, the incorporation of these properties makes the Au NPs have high solar energy conversion efficiencies, which are critical to the enhancement of clean energy technology. In fuel-cell technology, Au NPs work as catalysts to inspire oxidation reactions in fuel cells in order to generate electricity by using ordinary renewable fuels such as hydrogen. This application cuts out the need for conventional platinum catalysts that are expensive and derivative in nature. Au NPs also catalyze photocatalytic processes that break down organic compounds under sunlight for the biodegradation of wastewaters. This photocatalytic process can be considered as an environmentally friendly one in relation to conventional chemical treatments, as the solar energy is used to decompose the pollutants and, therefore, improve the ecological efficiency.[432] Additionally, Table 16 highlights the diverse applications of Au NPs in sustainable and green chemistry, detailing the materials' morphology, application areas, and key findings. The table illustrates how Au NPs, with their unique properties, play a

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pivotal role in environmentally friendly chemical processes, including catalysis, waste treatment, and energy conversion, offering promising alternatives for reducing the environmental impact of industrial processes.

5. CONCLUSION AND FUTURE PERSPECTIVES

Gold-based nanomaterials have emerged as a versatile class of materials with exceptional properties, enabling their application in diverse fields, such as biomedicine, catalysis, sensing, and energy storage. This Review highlights the various synthesis techniques, including chemical reduction, seed-mediated growth, green synthesis, and physical methods, each offering distinct advantages and limitations. While significant progress has been made in understanding the synthesis parameters and their influence on nanomaterial properties, challenges such as scalability, reproducibility, and environmental sustainability persist. Despite these challenges, gold-based nanomaterials hold immense promise for future innovations. Hybrid nanomaterials and functional surface modifications are anticipated to create new avenues toward tailored applications. Additionally, computational modeling combined with experimental techniques can speed up the design of gold-based nanostructures that are well-defined on the nanoscale. The future research will be focused on the development of greener and cost-effective and scalable synthesis processes that are environment friendly. In addition, novel functionalization strategies for gold nanomaterials have been explored to enhance their performance in specific applications. However, an in-depth mechanistic study is needed to elucidate their mechanisms pertaining to interaction with biological systems, catalytic efficiency, and stability under diverse conditions. The prospect is exciting in terms of theranostic, nanorobotics, and quantum technologies where gold-based nanomaterials can be leveraged. At present, the investigation of the gold-based nanomaterials, with strong ties to cooperation with other disciplines and development of the technologies, will probably revolutionize their use in all scientific and industrial fields, making them materials of utmost importance for modern nanotechnology.

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Notes

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