ACS OMEGA

http://pubs.acs.org/journal/acsodf

Review

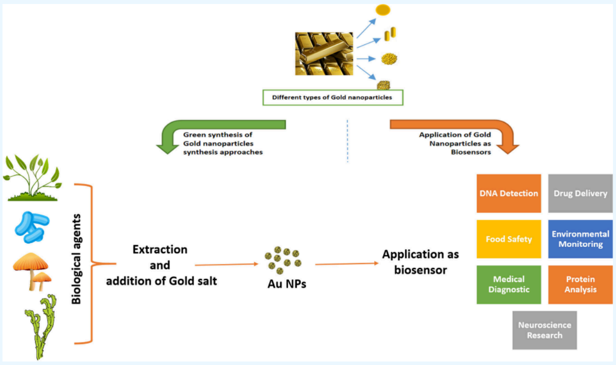
Gold Nanoparticles in Nanobiotechnology: From Synthesis to Biosensing Applications

Arun Karnwal,* Rohan Samir Kumar Sachan, Inderpal Devgon, Jyotsna Devgon, Gaurav Pant,* Mitali Panchpuri, Akil Ahmad, Mohammed B. Alshammari, Kaizar Hossain,* and Gaurav Kumar

Cite This: *ACS Omega* 2024, 9, 29966−29982

Read Online

ABSTRACT: Nanobiotechnology has ushered in a new era of scientific discovery where the unique properties of nanomaterials, such as gold nanoparticles, have been harnessed for a wide array of applications. This review explores gold nanoparticles' synthesis, properties, and multidisciplinary applications, focusing on their role as biosensors. Gold nanoparticles possess exceptional physicochemical attributes, including size-dependent optical properties, biocompatibility, and ease of functionalization, making them promising candidates for the development of biosensing platforms. The review begins by providing a comprehensive overview of gold nanoparticle synthesis techniques, highlighting the advantages and disadvantages of various approaches. It then delves into the remarkable properties that underpin their success in biosensing, such as localized surface plasmon resonance and enhanced surface area. The discussion also includes the functionalization strategies that enable specific binding to biomolecules, enhancing the sensitivity and selectivity of gold-nanoparticle-based biosensors. Furthermore, this review surveys the diverse applications of gold nanoparticles in biosensing, encompassing diagnostics, environmental monitoring, and drug delivery. The multidisciplinary nature of these applications underscores the versatility and potential of gold nanoparticles in addressing complex challenges in healthcare and environmental science. The review emphasizes the pressing need for further exploration and research in the field of nanobiotechnology, particularly regarding the synthesis, properties, and biosensing applications of gold nanoparticles. With their exceptional physicochemical attributes and versatile functionalities, gold nanoparticles present a promising avenue for addressing complex challenges in healthcare and environmental science, making it imperative to advance our understanding of their synthesis, properties, and applications for enhanced biosensing capabilities and broader scientific innovation.



1. INTRODUCTION

In recent years, nanotechnology has emerged as a dynamic and rapidly advancing field that has profound implications across a wide range of scientific domains. This field is characterized by the manipulation of matter on the nanoscale. Applications in a wide variety of fields, including energy, mechanics, magnetics, biomedicine, catalysis, electronics, and optics research, have been made possible as a result of this rapidly developing field.[1] Nanobiotechnology emerges as an integrative subdomain within this multidisciplinary landscape, bringing together the fundamentals of nanotechnology, biological sciences, chemical sciences, materials science, and physical sciences. To revolutionize the production or modification of nano-objects for a wide variety of applications, nanobiotechnology is primarily focused on the design and fabrication of nano-objects and bifunctional macromolecules.[2] As a result of their one-of-a-kind qualities and extraordinary adaptability, nanoparticles stand out as prominent entities among the vast array of nanomaterials that have captivated the imaginations of researchers and innovators.[3]

These morphological variations are essential in defining the distinctive chemical, physical, and optical properties of nanoparticles, which frequently differ significantly from those of their bulk counterparts.[4] Nanoparticles can manifest themselves in a variety of shapes, including spherical, triangular, and rod-shaped configurations. Production of nanoparticles, with a particular emphasis on the synthesis of nanoparticles from a wide variety of materials, is the primary focus of research efforts in nanotechnology to the present day. Gold, a prestigious noble metal

Received: December 25, 2023
Revised: June 15, 2024
Accepted: June 19, 2024
Published: July 5, 2024

https://doi.org/10.1021/acsomega.3c10352

that is well-known for its inertness and stability, has been revealed to be an intriguing candidate in this context. Since gold nanoparticles (GNPs) have the potential to be useful in a wide range of applications, including ultrasensitive chemical detection, cutting-edge optoelectronic devices, breakthrough biological sensors, and catalytic marvels, there has been a significant amount of interest in the scientific community regarding these particles.[5] Notable antibacterial properties, which are derived from the high surface area to volume ratio of metallic nanoparticles, have garnered a significant amount of attention.[6] These properties are among the characteristics that make metallic nanoparticles highly desirable. The escalating challenges posed by microbial resistance to conventional antibiotics and the emergence of resilient bacterial strains are particularly relevant to this surge of interest, which is particularly pertinent in light of the challenge.

Copper, aluminum, palladium, iron, titanium, gold, platinum, and silver are just some of the materials that have been the focus of research in the field of metallic nanoparticles. Each of these materials possesses unique properties and applications, and a number of them have been investigated.[7] In particular, gold has a long and illustrious history in the field of medicine. It has been used in a variety of applications for the treatment of a wide range of medical conditions, such as restorative dentistry, rheumatic illnesses, discoid lupus erythematosus, and skin inflammatory conditions like psoriasis, pemphigus, and urticaria at various points in time.[8] One of the most important steps in realizing the potential of gold nanoparticles across a variety of scientific fields is the synthesis of these particles. To facilitate the synthesis of these nanoparticles, researchers have utilized a wide variety of biological agents.[9] These biological agents include actinomycetes, fungi, plant tissues, bacteria, and a variety of biomolecules. Extracellular synthesis has emerged as a particularly effective and promising avenue among notable methods. It provides a path that circumvents multiple stages of the synthesis process, making it a particularly promising avenue.[10]

The “top-bottom” and “bottom-top” methods are the two primary approaches that are utilized in the process of synthesizing nanoparticles, respectively. Nanoparticles are produced by the bottom-top method, which involves the self-assembly of atom nuclei, resulting in the gradual development of nanoscale particles. Methods that involve organisms, such as plants and microbes, can be included in this approach. Chemical reduction processes can also be included. Through a variety of lithographic processes, the top-bottom method, on the other hand, is centered on the reduction of large materials into smaller particles. Traditional chemical and physical processes that are utilized in the production of nanoparticles are, however, subject to certain constraints. The use of toxic substances, which are not only economically burdensome but also pose significant risks to the environment and biological systems, is frequently a component of these methods.[11]

The field of biosensors has been entirely transformed by nanotechnology, which has made it possible to create devices that are both sensitive and selective in their ability to detect biological molecules and analytes. In the realm of nanomaterials used for the construction of biosensors, gold nanoparticles (AuNPs) have emerged as a tool that is both versatile and valuable. Because they make use of surface plasmon resonance, gold nanoparticles are significant biosensors that allow for sensitive detection without the need for labels. Because of their biocompatibility, straightforward functionalization, and signal amplification capabilities, they confer specificity as well as increased sensitivity. Their dependability for a wide variety of biosensor configurations, which are essential in medical diagnostics and environmental surveillance,[12] is a result of their stability, adjustability, and adaptability.[11] When it comes to biosensing applications, these minuscule particles of noble metals possess a set of physical and chemical characteristics that are one of a kind. This article discusses the importance of gold nanoparticles as biosensors. It describes their properties, how they can be used, and why they are so popular in diagnostics. By providing a comprehensive overview of the rapidly developing field of biosynthesis of gold nanoparticles, the purpose of this review is to shed light on the broad range of applications that these nanostructures offer across a variety of scientific fields such as biosensors.

2. GENERAL CHEMISTRIES OF GOLD (AURIC- (AU))

Gold, a fascinating element in the periodic table, exhibits a rich spectrum of oxidation states, encompassing six possible values ranging from −1 to +5.[13] This diversity arises from gold’s relatively high electronegativity, which dictates its propensity to engage in various chemical reactions. Among these oxidation states, Au(I) and Au(III) are the primary ones involved in the formation of gold complexes.[14] The dissolution of gold in aqueous solutions is an intricate process driven by oxidation and complexation phenomena. Complex ligands play a pivotal role in this process, enabling the formation of stable Au(I) and Au(III) complexes in solution, which can subsequently be reduced to produce metallic gold.[15] The stability of these gold complexes hinges on several factors, including the characteristics of the complex ligands and the nature of the donor atoms directly bonded to gold atoms.

Extensive research in gold chemistry has yielded valuable insights into the factors governing the stability of gold complexes. Two fundamental rules have emerged from these investigations, shedding light on the intricacies of gold complexation. First, as the donor atom’s electronegativity increases, the gold complexes’ stability generally decreases.[16] In solution, this principle is evident in the varying stability of gold halide complexes, with the order of stability being I− > Br− > Cl− > F.[17] Second, the choice of ligands can influence the oxidation state of gold in the complex. Harsh ligands tend to favor the formation of Au(III) complexes, while gentler ligands have a propensity for Au(I) complexes.[18] The favored coordination number of Au(I) compounds is 2, leading to a linear complex geometry, while the preferred coordination number of Au(III) complexes is 4, leading to a square planar geometry. In the realm of nanotechnology, gold nanoparticles (GNPs) have garnered significant attention due to their unique properties and wide-ranging applications.[19] The production of GNPs often relies on specific precursor compounds, and two of the most commonly employed precursors are gold(III) chloride complexes and gold thiosulfate(I). These precursors are the starting materials for various GNP synthesis techniques, including chemical and biological methods.[20]

Gold(III) chloride complexes are widely favored as precursors in GNP biosynthesis techniques. Due to their well-defined properties and reactivity, these complexes offer a robust platform for controlled nanoparticle synthesis. Their use in various synthetic approaches allows researchers to tailor GNP size, shape, and surface properties, thereby fine-tuning the nanoparticles for specific applications.[21] Moreover, gold(III) chloride complexes are amenable to surface modification,

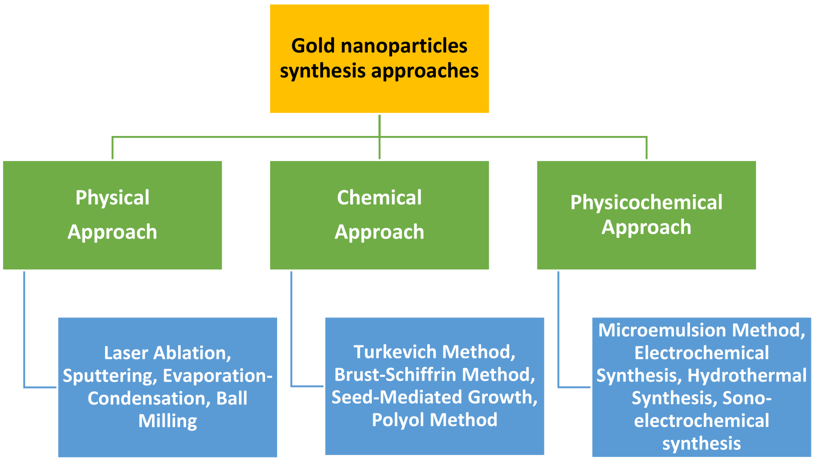


Figure 1. Various traditional approaches used for gold nanoparticle synthesis.

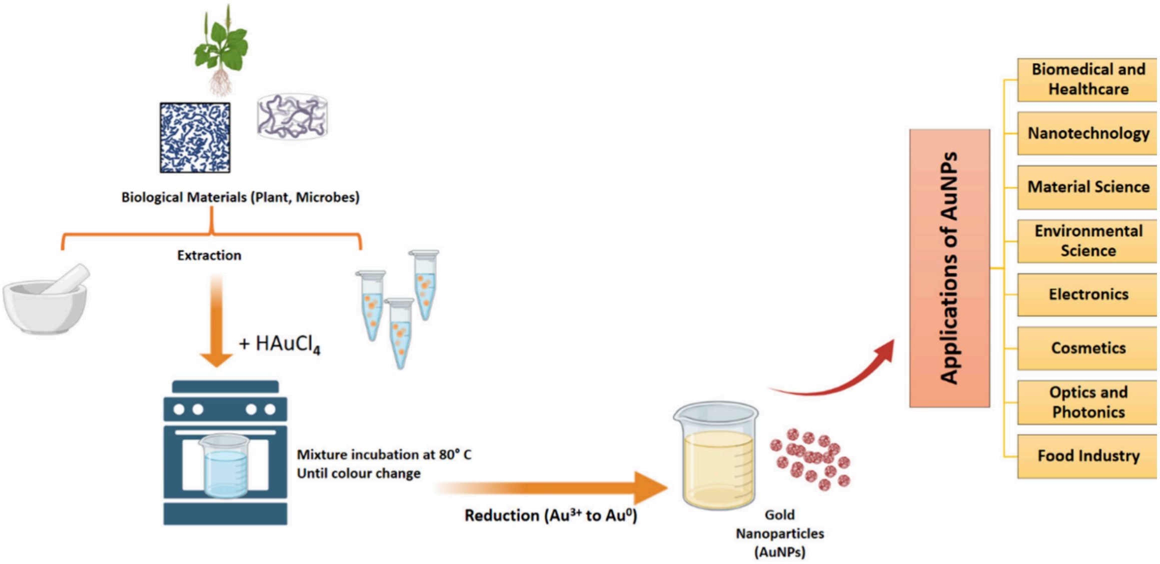


Figure 2. Biosynthesis of gold nanoparticles using various biological materials, i.e., plants, fungi, and bacteria.

enabling the attachment of functional groups that enhance the stability and biocompatibility of GNPs in biological and medical applications.[22] Gold's remarkable ability to adopt multiple oxidation states, particularly Au(I) and Au(III), underpins its utility in forming stable complexes, making it a valuable element in various chemical and nanotechnological applications. Understanding the principles governing the stability of gold complexes and the choice of precursor compounds is essential for advancing the field of nanotechnology and harnessing the unique properties of gold nanoparticles for diverse scientific and technological endeavors.

3. GREEN AND SUSTAINABLE NANOPARTICLE SYNTHESIS: A PROMISING SHIFT FROM TRADITIONAL METHODS TO BIOSYNTHESIS FOR ENHANCED CONTROL AND REDUCED ENVIRONMENTAL IMPACT

It has been technically difficult to produce gold nanoparticles (GNPs) with complete control over their phases and forms for a long time. About 150 years ago, Michael Faraday reported synthesizing gold colloids, now known as GNPs, using phosphorus to decrease the number of $AuCl_4$ ions. Since then, GNPs have been used in numerous other areas including electronics, biology, manufacturing, drugs, agriculture, and even medicine. Colloids, clusters, wires, powders, tubes, rods, and thin films, all with precisely controlled compositions, have been fabricated using various biological, physical, and chemical techniques.[23]

Historically, physical and chemical approaches have been used in synthesizing GNPs, as shown in Figure 1. Traditional synthesis techniques have significant drawbacks, despite years of study and technological development. They typically require more difficult ingredients, stringent synthesis conditions, greater energy or financial requirements, and fewer final products. In addition, costly and low-yield purifying methods, like differential centrifugation, are required to create mixed-shaped nanoparticles (NPs) by using these synthetic pathways. Because of the need to utilize potentially harmful solvents or additives, these purification techniques drive up costs and create substantial waste and environmental dangers. As a result, greener, safer, less harmful, and more long-lasting synthesis strategies are in high demand. The development of high-yield production processes that are also cost-effective is one of the most important difficulties facing the area of NP synthesis.

Table 1. Approaches Used for Gold Nanoparticle Synthesis

Synthesis Approach	Techniques	Advantages	Disadvantages
Physical approach	Laser ablation	Minimal chemical contamination, precise control over size and shape	Limited scalability
	Sputtering	High purity scalability	Lack of surface functionalization challenging to achieve narrow size distribution
	Evaporation		
	Ball milling		
Chemical approach	Turkevich method	Simple size control	Limited size control
	Brust−Schiffrin method	Monodispersity and stability	Limited scalability, non-biocompatible
	Seed-mediated growth	Good shape control	Complex and requires precise conditions
	Polyol method	High yield and size control	Polyol residues may affect applications
Physiochemical approach	Microemulsion method	Good size, control, and stability	Requires surfactants, potential contamination
	Electrochemical synthesis	Precise control and scalability	Limited to certain shapes, potential oxidation
	Sono-electrochemical synthesis	Efficient	Equipment complexity

Table 2. Plant Species Used for Gold Nanoparticle Synthesis, along with Nanoparticle Size, Shape, and Application

Plant	Plant Part Used	Nanoparticle Size	Nanoparticle Shape	Applications	References
Aloe vera	Leaf extract	20−50 nm	Spherical	Biomedical (drug delivery, imaging)	28
Green tea	Leaf extract	10−30 nm	Spherical	Antioxidant, drug delivery	
Turmeric	Rhizome extract	10−50 nm	Spherical	Antibacterial, wound healing	
Neem	Leaf extract	5−30 nm	Spherical	Antimicrobial, insect repellent	
Hibiscus	Flower extract	20−60 nm	Spherical	Food packaging, water purification	29
Grapefruit	Peel extract	10−40 nm	Spherical	Anticancer, antioxidant	
Lemon	Peel extract	15−50 nm	Spherical	Antimicrobial sensor development	
Pomegranate	Peel extract	10−40 nm	Spherical	Antioxidant, drug delivery	
Rosemary	Leaf extract	20−60 nm	Spherical	Antioxidant, antibacterial	
Garlic	Bulb extract	10−30 nm	Spherical	Antimicrobial drug delivery	
Ginger	Rhizome extract	10−40 nm	Spherical	Anti-inflammatory, drug delivery	
Onion	Bulb extract	5−30 nm	Spherical	Anticancer, sensor development	30
Cinnamon	Bark extract	10−50 nm	Rod-shaped	Antioxidant, drug delivery	
Basil	Leaf extract	20−60 nm	Spherical	Antimicrobial drug delivery	
Eucalyptus	Leaf extract	5−30 nm	Spherical	Antimicrobial sensor development	31
Spinach	Leaf extract	10−40 nm	Spherical	Antioxidant, drug delivery	
Papaya	Fruit extract	10−30 nm	Spherical	Antioxidant, wound healing	
Lavender	Flower extract	20−50 nm	Spherical	Aromatherapy, drug delivery	
Chamomile	Flower extract	10−30 nm	Spherical	Anti-inflammatory, sensor development	
Thyme	Leaf extract	10−40 nm	Spherical	Antibacterial drug delivery	
Black pepper	Fruit extract	5−30 nm	Spherical	Antioxidant, drug delivery	32
Clove	Bud extract	10−50 nm	Spherical	Antibacterial dental applications	
Olive	Leaf extract	10−30 nm	Spherical	Antioxidant, drug delivery	
Coconut	Shell extract	20−60 nm	Spherical	Antimicrobial, water purification	
Walnut	Shell extract	10−40 nm	Spherical	Antioxidant, drug delivery	
Mango	Peel extract	10−30 nm	Spherical	Antioxidant, food packaging	
Banana	Peel extract	5−30 nm	Spherical	Food packaging, wound healing	
Orange	Peel extract	10−50 nm	Spherical	Antioxidant, drug delivery	
Sugar cane	Bagasse extract	20−60 nm	Spherical	Water purification, sensor development	
Pineapple	Peel extract	10−40 nm	Spherical	Food packaging, drug delivery	

This imperative has led researchers to explore biological systems as a promising alternative. As illustrated in Figure 2, Biosynthesis has emerged as a viable and sustainable approach for the large-scale production of nanoscale particles, including GNPs. Notably, NPs produced through biological methods exhibit enhanced stability and superior control over their morphological attributes.

Biological systems, ranging from bacteria and fungi to actinomycetes and plants, have demonstrated the ability to produce NPs. Microbes, in particular, can produce intracellular and extracellular NP due to their intrinsic capabilities.[24] However, extracting NPs generated through intracellular biosynthesis can be challenging, necessitating additional processing steps, such as ultrasonication or treatment with suitable detergents. Therefore, for practical applications, bacteria that extracellularly produce NPs must undergo rigorous screening to identify suitable candidates for GNP production.[25] The exploration of microbes as possible biofactors for the synthesis of GNP offers a promising area of research. The methodology mentioned above presents numerous benefits, encompassing the ability to accommodate larger-scale production, cost-effectiveness, time efficiency, and environmental

Table 3. Algae Species Commonly Used for Gold Nanoparticle Synthesis, along with Information on the Nanoparticle Size, Shape, and Applications

Algae Species	Nanoparticle Size (nm)	Nanoparticle Shape	Applications	References
Chlorella vulgaris	20−50	Spherical	Drug delivery, cancer therapy, biosensors	36
Spirulina platensis	10−100	Rod-shaped	Antimicrobial coatings, nanocomposites	37
Dunaliella salina	5−30	Spherical	Biomedical imaging, drug delivery	
Nannochloropsis sp.	20−80	Spherical	Photothermal therapy, nanoelectronics	
Scenedesmus sp.	10−60	Spherical	Catalysis, nanofabrication	
Porphyridium sp.	5−40	Spherical	Drug delivery, biosensors	
Nostoc commune	30−80	Spherical	Environmental sensors, water purification	38
Botryococcus braunii	10−50	Spherical	Photovoltaics, energy storage	
Rhodomonas sp.	5−25	Spherical	Food packaging, cosmetics	
Chlorococcum sp.	10−70	Spherical	Nanocomposite materials, optics	
Cyanidioschyzon merolae	5−30	Spherical	Nanomedicine, gene therapy	27
Amphora sp.	20−60	Spherical	Conductive inks, electronics	
Haematococcus pluvialis	10−50	Spherical	Antioxidant, antiaging cosmetics	
Microcystis aeruginosa	10−40	Spherical	Water purification, environmental sensors	
Tetraselmis suecica	5−25	Spherical	Food safety, environmental monitoring	
Ankistrodesmus sp.	10−50	Spherical	Catalytic converters, environmental remediation	39
Phaeodactylum tricornutum	5−30	Spherical	Photodetectors, plasmonic devices	
Neochloris oleoabundans	10−60	Spherical	Solar cells, energy storage	
Chlamydomonas reinhardtii	10−40	Spherical	Biosensors, environmental monitoring	40
Euglena gracilis	10−60	Spherical	Nanomedicine, drug delivery	
Navicula sp.	20−80	Rod-shaped	Nanocomposite materials, sensors	
Isochrysis sp.	10−50	Spherical	Food additives, nanofabrication	
Phormidium sp.	10−40	Spherical	Antibacterial coatings, environmental sensors	
Heterosigma akashiwo	5−30	Spherical	Nanomedicine, drug delivery	
Tetraselmis chuii	10−60	Spherical	Photothermal therapy, environmental sensors	
Lyngbya sp.	20−80	Filamentous	Art conservation, environmental remediation	
Chondrus crispus	10−40	Spherical	Food packaging, cosmetics	
Gelidium corneum	5−30	Spherical	Antimicrobial coatings, drug delivery	41
Gracilaria sp.	10−60	Spherical	Biomedical imaging, nanocomposites	
Pseudanabaena sp.	10−40	Spherical	Water purification, environmental sensors	
Oscillatoria sp.	20−80	Filamentous	Environmental remediation, nanofabrication	

sustainability.[26] The following sections comprehensively examine diverse microbial production methods for gold nanoparticles (GNPs), elucidating the underlying principles and their possible uses.

The quest for controlled synthesis of nanoscale gold particles, particularly GNPs, has driven the exploration of various physical and chemical methods over the years. However, these conventional approaches suffer from limitations related to their environmental impact, cost, and scalability. In response to these challenges, biosynthesis has emerged as an attractive alternative, harnessing the inherent capabilities of biological systems to produce GNPs with enhanced stability and precise control over their morphological features. Using microorganisms as biofactories for GNP production holds immense promise for achieving high-yield, cost-effective, and environmentally friendly synthesis methods. The subsequent sections will delve into the intricacies of microbial synthesis techniques, unveiling their potential to revolutionize GNP production.

3.1. Plants. One of the most significant breakthroughs in nanotechnology is the biosynthesis of nanoparticles, a technique that harnesses the remarkable potential of plant extracts (refer to Figure 2). This innovative approach revolutionizes how we create nanoparticles and offers numerous ecological advantages that make it a promising avenue for sustainable nanomaterial production. *Azadirachta indica* leaf extract demonstrated its prowess in a noteworthy investigation facilitating the bioreduction of Au^{3+} or Ag^{+} ions (Table 2).[27] This process involves the transformation of gold and silver ions into nanoparticles through the action of compounds found in the plant extract. *Aloe vera* leaf extract has also been instrumental in crafting intricate gold nanotriangles and spherical silver nanoparticles (Table 1).[28] These achievements underscore the versatility and potential of plant-based synthesis techniques. Utilizing nontoxic biocomponents from plant extracts to cap or reduce these nanoparticles minimizes waste generation and eliminates the need for additional purification steps, thereby enhancing accessibility while reducing the environmental footprint.

The active involvement of various biocomponents found in plant extracts, such as flavonoids, phytosterols, and quinones, plays a pivotal role in the generation of nanoparticles.[29] These compounds possess functional groups that aid in reducing and stabilizing the resulting nanoparticles. The achievement of specific shapes and sizes of nanoparticles depends on carefully manipulating the reaction parameters, including pH, incubation duration, and temperature. An investigation by Song et al. demonstrated the production of gold nanoparticles using leaf extracts derived from two distinct plant species, namely, *Magnolia kobus* and *Diospyros kaki*.[30] By amalgamating these extracts with an aqueous $HAuCl_4$ solution while upholding a reaction temperature of 95 °C, the researchers successfully attained a remarkable yield exceeding 90% of the intended gold nanoparticles within a brief period.[31]

Similarly, the fruit extract of *Emblica officinalis* demonstrated significant efficacy as a reducing agent in the extracellular

Table 4. Fungi Commonly Used for Gold Nanoparticle Synthesis, along with Information about the Nanoparticle Size, Shape, and Potential Applications

Fungal Species	Nanoparticle Size (nm)	Nanoparticle Shape	Potential Applications	References
Agaricus bisporus	5−25	Spherical	Catalysis, drug delivery	45
Amanita muscaria	10−30	Spherical	Nanocomposite materials, conductive inks	
Aspergillus niger	5−20	Spherical	Biosensors, antimicrobial coatings	
Auricularia auricula	10−60	Spherical	Antioxidant agents, biosensors	
Auricularia spp.	5−20	Spherical	Food additives, sunscreen	
Candida albicans	5−15	Spherical	Antifungal coatings, drug delivery	48
Candida tropicalis	5−30	Spherical	Antibacterial coatings, sensors	
Cladosporium cladosporioides	5−20	Spherical	Environmental monitoring, sensors	49
Cordyceps spp.	20−70	Rods	Energy storage, photodetectors	
Cryptococcus neoformans	5−30	Spherical	Antifungal agents, biosensors	
Fomes fomentarius	10−50	Spherical	Environmental remediation, optics	50
Fusarium oxysporum	10−30	Spherical	Cancer therapy, nanoelectronics	
Ganoderma lucidum	5−30	Spherical	Biomedical imaging, drug delivery	
Ganoderma spp.	10−50	Irregular	Cosmetics, antiviral agents	
Gliocladium roseum	15−45	Spherical	Biomedical imaging, catalysis	
Laccaria spp.	10−30	Spherical	Environmental monitoring, nanofabrication	
Lentinula edodes	10−35	Spherical	Food safety, drug delivery	51
Mucor spp.	15−45	Spherical	Food packaging, nanofabrication	52
Myrothecium verrucaria	10−40	Spherical	Nanoelectronics, gene therapy	53
Neurospora crassa	5−30	Spherical	Nanoelectronics, photodetectors	
Penicillium sp.	20−80	Rods	Environmental remediation, sensors	54
Penicillium spp.	10−60	Spherical	Anticancer agents, catalysis	
Phanerochaete chrysosporium	20−60	Spherical	Bioremediation, wastewater treatment	55
Phellinus spp.	10−60	Irregular	Drug delivery, nanocomposites	56
Pleurotus eryngii	10−40	Irregular	Nanomedicine, nanofabrication	57
Pleurotus florida	10−40	Spherical	Nanosensors, drug delivery	
Pleurotus ostreatus	10−40	Spherical	Biomedical coatings, sensors	
Pleurotus sajor-caju	10−40	Spherical	Environmental remediation, sensors	
Pseudallescheria boydii	10−50	Spherical	Drug delivery, wound healing	
Rhizopus oryzae	10−25	Spherical	Nanocomposites, optics	47
Saccharomyces cerevisiae	10−40	Spherical	Bioimaging, food safety	
Schizophyllum commune	15−45	Spherical	Art conservation, catalysis	
Tolypocladium ophioglossoides	20−60	Spherical	Environmental sensors, catalysis	
Trametes versicolor	10−30	Spherical	Water purification, photothermal therapy	
Tremella spp.	15−50	Spherical	Biomedical coatings, optics	46
Trichoderma harzianum	10−40	Spherical	Biomedical imaging, drug delivery	
Trichoderma sp.	10−50	Spherical	Drug delivery, catalysis	

manufacture of silver nanoparticles with exceptional stability.[33] In a separate investigation, scholars utilized an extract derived from *Cinnamomum camphora* leaves to effectively fabricate gold nanoparticles, thereby highlighting the adaptability of this particular approach.[34] To provide a comprehensive overview of the specific plant sources used for GNP synthesis, we compiled detailed information in Table 1. This information will serve as a valuable resource for researchers seeking to explore the vast potential of plant-based biosynthesis techniques for nanoparticles, opening new doors to sustainable and environmentally friendly nanomaterial production. The convergence of biology and nanotechnology through plant extracts promises a brighter and more sustainable future for nanoparticle synthesis.

3.2. Algae. Algae, the diverse group of photosynthetic organisms found in aquatic environments, have garnered significant attention in recent years as promising biological agents for the eco-friendly synthesis of various nanoparticles, as mentioned in Table 3. This burgeoning field of research focuses on exploiting the unique properties of algae to facilitate the production of metal nanoparticles. Specifically, scientists are delving into how various reaction conditions, including pH, temperature, and stirring rate, can influence the characteristics of the resulting nanoparticles, such as their size, morphology, stability, and other pertinent properties. One captivating avenue of exploration involves harnessing algae to mediate the synthesis of gold nanoparticles (GNPs).[35] These studies have unveiled fascinating insights into the interplay between algae and gold ions during nanoparticle formation. In one notable investigation, *Chlorella vulgaris* biomass was employed to reduce gold(III) to gold(I) ions from a gold chloride solution, as corroborated by X-ray absorption spectroscopy (XAS) data (Table 2). This study revealed the coordination of Au(I) ions with sulfur atoms, likely originating from free-sulfhydryl residues or lighter atoms, possibly nitrogen.[36]

A few algal species used for gold nanoparticle synthesis are mentioned in Table 2. In another intriguing study, the interaction between elemental gold and *Sargassum natans* biomass led to the predominant precipitation of gold on the alga's cell walls.[37] This phenomenon was attributed to the strong binding of gold ions to hydroxyl groups in saccharides or carboxylate anions found in amino acid residues from peptidoglycan layers on the alga's cell walls. The marine alga

Table 5. Bacteria Commonly Used for Gold Nanoparticle Synthesis, along with Information about the Nanoparticle Size, Shape, and Their Applications

Bacteria Species	Nanoparticle Size (nm)	Nanoparticle Shape	Potential Applications	References
Acinetobacter baumannii	5−30	Spherical	Drug delivery, antimicrobial coatings	60
Alcaligenes faecalis	10−50	Spherical	Environmental remediation, catalysis	61
Bacillus licheniformis	5−25	Spherical	Antibacterial agents, wound healing	62
Bacillus subtilis	5−30	Spherical	Antibacterial agents, bioimaging, catalysis	63
Bifidobacterium breve	5−40	Spherical	Probiotic delivery, food industry	64
Burkholderia pseudomallei	10−50	Spherical	Biomedical imaging, biosensors	65
Campylobacter jejuni	5−30	Spherical	Food safety, biosensors	66
Chlamydia trachomatis	5−30	Spherical	Drug delivery, diagnostics	67
Clostridium acetobutylicum	10−60	Spherical/Rod-shaped	Biofuel production, catalysis	68
Clostridium pasteurianum	10−60	Spherical	Bioremediation, catalysis	
Corynebacterium glutamicum	5−30	Spherical	Industrial biotechnology, biosensors	69
Cupriavidus metallidurans	10−60	Spherical/Rod-shaped	Environmental remediation, catalysis	
Desulfotomaculum reducens	10−60	Spherical/Rod-shaped	Bioremediation, environmental sensing	
Desulfovibrio desulfuricans	10−60	Spherical/Rod-shaped	Bioremediation, environmental sensing	
Desulfovibrio vulgaris	10−60	Spherical/Rod-shaped	Bioremediation, environmental monitoring	
Enterobacter aerogenes	10−50	Spherical	Environmental cleanup, catalysis	
Enterobacter cloacae	5−40	Spherical	Drug delivery, environmental monitoring	
Enterococcus faecium	5−40	Spherical	Antibacterial coatings, food safety	70
Escherichia coli (E. coli)	5−50	Spherical	Drug delivery, biosensors, catalysis	
Geobacter sulfurreducens	10−60	Spherical/Rod-shaped	Environmental cleanup, biosensors	
Helicobacter pylori	5−30	Spherical	Drug delivery, gastrointestinal diagnostics	
Klebsiella pneumoniae	5−30	Spherical	Drug delivery, biosensors	
Lactobacillus acidophilus	10−40	Spherical	Drug delivery, food packaging	58
Lactobacillus plantarum	5−40	Spherical	Food packaging, biosensors	
Lactobacillus rhamnosus	5−40	Spherical	Probiotic delivery, food industry	
Lactococcus lactis	10−40	Spherical	Food industry, drug delivery	
Legionella pneumophila	5−30	Spherical	Water quality monitoring, biosensors	71
Listeria monocytogenes	5−40	Spherical	Food safety, drug delivery	
Mycobacterium smegmatis	5−30	Spherical	Drug delivery, tuberculosis diagnostics	
Mycobacterium tuberculosis	5−30	Spherical	Tuberculosis diagnostics, drug delivery	
Pediococcus acidilactici	5−40	Spherical	Food industry, drug delivery	
Propionibacterium acnes	5−25	Spherical	Acne treatment, drug delivery	
Proteus mirabilis	5−25	Spherical	Drug delivery, antimicrobial coatings	72
Pseudomonas aeruginosa	5−40	Spherical	Bioremediation, wound healing	
Pseudomonas putida	10−50	Spherical	Bioremediation, environmental monitoring	
Rhizobium leguminosarum	10−50	Spherical	Agriculture, soil remediation	
Rhodobacter sphaeroides	10−40	Spherical/Rod-shaped	Photovoltaics, photocatalysis	36
Rhodopseudomonas capsulata	10−40	Spherical/Rod-shaped	Photocatalysis, biosensors	
Salmonella enterica	5−30	Spherical	Food safety, drug delivery	
Shewanella oneidensis	10−60	Spherical/Rod-shaped	Environmental cleanup, water purification	
Shigella flexneri	5−30	Spherical	Drug delivery, biosensors	
Staphylococcus aureus	5−25	Spherical	Antimicrobial coatings, imaging	59
Streptococcus mutans	5−25	Spherical	Dental materials, bioimaging	
Streptococcus pneumoniae	5−25	Spherical	Vaccine development, bioimaging	
Streptococcus pyogenes	5−25	Spherical	Antibacterial agents, bioimaging	
Streptococcus salivarius	5−30	Spherical	Oral healthcare, bioimaging	
Streptococcus thermophilus	10−50	Spherical	Drug delivery, food industry	
Vibrio cholerae	5−30	Spherical	Biosensors, water quality monitoring	73

Sargassum wightii also made waves in the realm of gold nanoparticle synthesis. Researchers successfully produced stable GNPs, ranging in size from 8 to 12 nm, by reducing aqueous $AuCl_4^-$ ions within extracts of this marine alga.[38] Astonishingly, this method achieved an impressive 95% gold recovery, highlighting its eco-friendly and efficient nature. This success with *Sargassum wightii* has catalyzed further exploration into other algae species for GNP synthesis.[42] Among these are *Laminaria japonica*, *Sargassum wightii*, *Stoechospermum marginatum*, *Sargassum myriocystum*, *Chlorella pyrenoidosa*, *Kappaphycus alvarezii*, and *Acanthophora spicifera* all of which have exhibited promise in this regard.[43]

For instance, Arockiya Aarthi Rajathi et al.[39] conducted research involving *Stoechospermum marginatum*, resulting in the synthesis of gold nanoparticles with sizes spanning from 18.7 to 93.7 nm. According to another intriguing study, *Tetraselmis kochinensis* was used to successfully synthesize gold nanoparticles, with the resulting particles ranging in size from 5 to 35 nm.[139] Abdel-Raouf et al.[40] explored the potential of *Galaxaura elongata* for GNP synthesis, leading to the production of nanoparticles spanning an intriguing size range of 3.85 to 77.13 nm.[40] Furthermore, Costa et al. contributed to this evolving field by reporting the synthesis of gold nanoparticles using *Sargassum cymosum*, which exhibited sizes varying from 7 to 20 nm.[44] The synthesis of gold nanoparticles through the mediation of various algae species is a burgeoning and dynamic field of research. These studies shed light on the fascinating interaction between algae and gold ions and hold great promise for eco-friendly nanoparticle production processes with wide-ranging applications in fields such as medicine, catalysis, and materials science. As further scientific exploration unfolds, the potential of algae as bio templates for nanoparticle synthesis continues to captivate researchers and offers exciting prospects for sustainable nanotechnology.

3.3. Fungi. Fungi have emerged as highly efficient microorganisms for synthesizing metal nanoparticles, particularly gold nanoparticles (GNPs). This remarkable capability has attracted significant attention from researchers seeking sustainable and eco-friendly methods for nanoparticle production. Several fungal species, such as *Phoma glomerata*, *Aspergillus fumigatus*, *Coriolus versicolor*, *Fusarium semitectum*, *Fusarium oxysporum*, *T. viride*, *Trichothecium* sp., *Phanerochaete chrysosporium*, *Trichoderma asperellum*, and *Colletotrichum* sp., have been identified as exemplary candidates for this purpose.[41] One of the key advantages of employing fungi in GNP synthesis is their resilience under harsh bioreactor conditions. Fungal mycelial networks exhibit exceptional durability, withstanding factors like flow pressure and agitation, which can be detrimental to bacterial counterparts.[45] Moreover, fungi are known for their ease of cultivation and management, making them an attractive choice for large-scale production.

The fungus species *Trichothecium* sp. holds significance in the field of GNP synthesis. The fungus exhibited the capacity to generate gold nanoparticles (GNPs) through extracellular and intracellular mechanisms. Under conditions of stasis, when subjected to gold ions, the biomass of *Trichothecium* sp. fungus engages with the ions, leading to the expeditious synthesis of gold nanoparticles (GNPs) outside the fungal cells in diverse geometries, such as spheres, rods, and triangles.[46] Conversely, when the fungal culture experiences agitation, intracellular GNP formation becomes prominent. Additionally, a study involving the extremophilic actinomycete *Thermomonospora* sp. reported its capacity to reduce metal ions extracellularly upon exposure to gold ions.[47] This fungal-mediated GNP synthesis offers a sustainable and scalable alternative to conventional chemical methods. The ease of downstream processing, driven by the substantial production of reductive protein extracellular secretions by fungi, further underscores the potential of fungal-based approaches in the field of nanoparticle synthesis.

Table 4 summarizes GNP production methods facilitated by fungi, highlighting their diverse shapes and synthesis conditions. These findings contribute to the expanding knowledge of nanobiotechnology and hold promise for various applications in medicine, electronics, and environmental remediation. Ongoing research continues to unveil the intricate mechanisms underlying fungal GNP synthesis, paving the way for innovative and sustainable nanotechnology solutions.

3.4. Bacteria. Prokaryotic microorganisms, particularly bacteria, have emerged as prominent players in the fascinating realm of gold nanoparticle (GNP) synthesis. This intriguing field has garnered significant attention due to its potential applications in various scientific and technological domains. The ability of prokaryotes to biologically synthesize GNPs has opened up exciting possibilities for controlled nanoparticle production with unique characteristics. This article delves into prokaryotes' diverse and remarkable contributions to the synthesis of GNPs, highlighting key findings and mechanisms. The pioneering work in bacterial GNP production was reported in *Bacillus subtilis*, unveiling octahedral GNPs with sizes spanning from 10 to 35 nm within the cell wall.[58] This discovery marked the inception of microbial GNP synthesis research. Subsequently, *Rhodopseudomonas capsulata* was found to produce spherical GNPs with diameters ranging from 10 to 20 nm at lower concentrations.[35] Remarkably, at higher concentrations this bacterium exhibited the formation of GNP nanowire networks. Further investigations expanded the list of GNP-producing cyanobacteria to include *Plectonema* sp., *Calothrix* sp., *Anabaena* sp., and *Leptolyngbya* sp. Additionally, the utilization of a single-celled protein, *Spirulina platensis*, demonstrated its potential for GNP synthesis.[59]

Table 5 provides a comprehensive summary of bacterial gold nanoparticle (GNP) synthesis, including several species and their unique characteristics with their application in producing nanoparticles. Ahmad et al.[47] did a pioneering study demonstrating the microbial synthesis of monodispersed gold nanoparticles (GNPs) using extremophilic *Thermomonas sp.*[47] Their research finding demonstrated that *Rhodopseudomonas capsulata* synthesized spherical gold nanoparticles (GNPs) within the size range of 15−25 nm.[35] This synthesis occurred following a 48-h incubation period with an aqueous chloroauric acid ($HAuCl_4$) solution with pH levels ranging from 4.0 to 7.0.[59] Notably, the pH of the solution played a crucial role in determining the types of biogenic AuNPs generated and the specific site of gold deposition within the bacterial cell. It is worth mentioning that the halotolerant *Rhodococcus* sp. has shown a tendency to produce intracellular monodispersed gold nanoparticles (GNPs) predominantly on the cytoplasmic membrane, as opposed to the cell walls.[35] The observed effect was ascribed to the activity of metal-ion-reducing enzymes found in the cell walls or on the cytoplasmic membrane but significantly lacking in the cytosol. In an alternative and captivating methodology, the liquid portion of *Pseudomonas aeruginosa* cells was utilized as a reductive substance for gold ions, resulting in the external generation of gold nanoparticles (GNPs).[72] In the process under consideration, it is noteworthy that heterotrophic sulfate-reducing bacteria played a crucial role in the reduction of gold(I) thiosulfate complexes ($(Au(S_2O_3)_2)$) into elemental gold particles with dimensions of around 10 nm.[74] Simultaneously, these bacteria produced hydrogen sulfide (H_2S) as a metabolic byproduct.

Escherichia coli DH5 demonstrated a notable capacity to enzymatically decrease chloroauric acid, forming gold nanoparticles predominantly on the cell's outer membrane.[75] The nanoparticles demonstrated a wide range of forms, such as spheres, triangles, and quasi-hexagons, which present a favorable potential for utilization in the hemoglobin or protein electrochemistry.[76] In addition, it has been observed that *Rhodobacter capsulatus*, a bacterium capable of photosynthesis, exhibits an enhanced ability to adsorb $HAuCl_4$ and demonstrates the capability to reduce trivalent gold.[77] The involvement of carotenoids and NADPH-dependent enzymes, whether integrated into plasma membranes or discharged into the extracellular environment, has been recognized as crucial in the biosorption and bioreduction mechanisms of Au^{3+} to Au^0.[78] These processes occur both internally and externally in bacterial cells. The world of prokaryotes has provided us with a

Table 6. Approaches for Biological Processes Involved in the Synthesis of Gold Nanoparticles

Biological Source	Synthesis Technique	Advantages	Challenges
Plant	Phytochemical reduction	Environmentally friendly, readily available source	Variability in plant extracts, slower synthesis
Algae	Algal extracts or biomass-mediated	Rapid synthesis, natural abundance, sustainable	Influence of growth conditions on nanoparticles size
Fungi	Fungal-mediated	Controlled synthesis, tunable size, and shape	Limited understanding of fungal mechanisms
Bacteria	Bacterial-mediated	Rapid synthesis, controlled size, ease of handling	Limited scalability, potential contamination

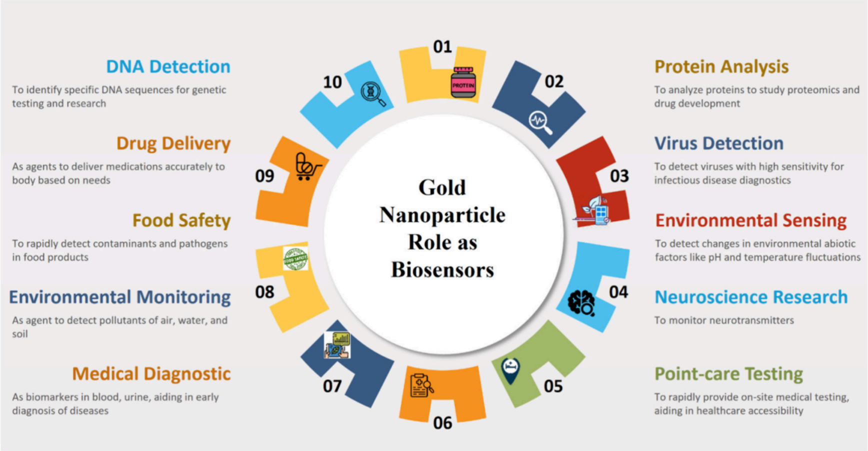


Figure 3. Overall application of gold nanoparticles as biosensors.

captivating glimpse into the synthesis of gold nanoparticles, showcasing a remarkable array of mechanisms and species involved. These findings enrich our understanding of microbial biology and hold immense promise for applications in fields ranging from nanotechnology to biotechnology. As research in this domain continues to advance, the potential for harnessing the unique capabilities of prokaryotes in GNP synthesis remains an exciting avenue for exploration and innovation.

Table 6 outlines various biological approaches for synthesizing gold nanoparticles. Plant-based phytochemical reduction is environmentally friendly and uses readily available sources, but it faces variability in extracts and slower synthesis. Algae utilize algal extracts or biomass-mediated techniques for rapid and sustainable synthesis, although growth conditions can affect the nanoparticle size. Fungal-mediated methods offer controlled synthesis with tunable size and shape, yet the mechanisms are not fully understood. Bacterial-mediated synthesis provides rapid production with controlled size and ease of handling, but scalability and potential contamination remain challenges.

4. GOLD NANOPARTICLE APPLICATIONS IN BIOSENSORS

Gold nanoparticles exhibit several distinct properties that make them excellent candidates for biosensors:

- **Surface Plasmon Resonance (SPR):** One of the most remarkable properties of gold nanoparticles is their ability to exhibit a phenomenon known as surface plasmon resonance (SPR). SPR is a collective oscillation of electrons on the nanoparticle's surface when illuminated with specific wavelengths of light. This property allows researchers to tune gold nanoparticles' absorbance and scattering spectra by controlling their size and shape. It is particularly useful in detecting minute changes in the local refractive index of the surrounding medium, which is crucial for biosensing applications.[79]
- **High Surface Area:** Gold nanoparticles have a high surface area-to-volume ratio, which means they can carry many biomolecules on their surface. This property is vital for enhancing the sensitivity of biosensors by providing a large area for binding target molecules.[80] Fungal-based synthesis methods are known to produce gold nanoparticles with high surface area characteristics. Fungal-assisted synthesis frequently enables precise control over the development and shape of gold nanoparticles, resulting in a greater surface area in comparison to plants, algae, or bacteria. Controlling the size and form of nanoparticles through fungal-mediated synthesis enhances the surface area of gold nanoparticles, making them ideal for applications such as catalysis and sensing.[81]
- **Biocompatibility:** Gold is generally considered biocompatible and nontoxic, making gold nanoparticles suitable for biological applications. They can be functionalized with various biomolecules, such as antibodies, DNA, and peptides, without compromising their biocompatibility.[82]

Using gold nanoparticles (AuNPs) in biosensors has significantly transformed diagnostics and detection (Figure 3). The nanoscale gold particles possess distinct characteristics that render them suitable for various biosensing applications. Gold nanoparticles (AuNPs) can undergo functionalization by attaching certain biomolecules, such as antibodies, DNA probes, or aptamers.[83] This functionalization allows for the highly selective and sensitive detection of target analytes. One of the notable characteristics of the subject under discussion is its exceptional optical qualities. Gold nanoparticles (AuNPs) demonstrate a phenomenon known as surface plasmonic resonance (SPR), resulting in alterations in their absorbance and scattering characteristics upon interaction with molecules or undergoing aggregation.[84,85] The importance of localized surface plasmon resonance (LSPR) and the larger surface area in gold nanoparticles for biosensing applications is due to their cumulative impact on sensitivity, label-free detection, and signal amplification. LSPR provides accurate and real-time tracking of biomolecular interactions, allowing for the identification of low analyte levels without requiring extra labels.[86] The large surface area of gold nanoparticles enables the attachment of many biomolecules, leading to an increased signal amplification and sensitivity. This adaptable surface area also supports the creation of multiplexed biosensors, allowing for the simultaneous detection of numerous analytes.[87] Combining LSPR and increased surface area makes gold nanoparticles a flexible and strong foundation for biosensing applications, providing benefits in sensitivity, specificity, and versatility for many diagnostic and analytical uses. LSPR's lack of labeling simplifies tests and minimizes unwanted interferences. The increased surface area allows for multifunctional functionalization, improving the biosensor selectivity necessary for selective interactions with many targets. Gold nanoparticles have unique features that make them highly effective in biosensing applications, particularly for the early identification and detection of low levels of biomarkers in different biological samples.[88]

Gold nanoparticles (AuNPs) are frequently employed as signal transducers in biosensing.[22] The binding of the target analyte to the functionalized gold nanoparticles (AuNPs) results in alterations in the local refractive index and the interparticle distance.[89] The modifications in the surrounding conditions of the nanoparticle lead to a modification in the wavelength of their surface plasmonic resonance (SPR) or a variation in their visual appearance, which can be detected or measured using spectroscopic methods.[90] The optical response described here is the fundamental principle behind numerous colorimetric and plasmonic biosensors. The utilization of gold nanoparticles (AuNPs) in biosensors has been recognized as a significant advancement, particularly in disease biomarker detection.[91,92] Assays utilizing gold nanoparticles (AuNPs) that have been modified with antibodies targeting certain proteins or antigens have been created by researchers. When the biomarkers are detected within a patient's sample, they exhibit an affinity toward the AuNPs, resulting in their aggregation and subsequent observable alteration in color.[93,94] This change can be conveniently monitored. The methodology mentioned above has been employed in timely identification of ailments such as cancer, HIV, and diverse infectious pathogens. DNA and RNA sensing is an additional significant use. Gold nanoparticles (AuNPs) can undergo functionalization by attaching single-stranded DNA or RNA probes that possess complementarity to a particular target sequence.[95,96] The aggregation and shift in the surface plasmon resonance (SPR) wavelength occur when the AuNPs' probes hybridize with the target DNA or RNA. This facilitates the identification of genetic mutations or infections or the measurement of nucleic acids.

Gold nanoparticles (AuNPs) have been widely utilized in electrochemical biosensors owing to their exceptional electrical conductivity and large surface area.[47] These characteristics render them highly suitable for immobilizing enzymes or other biorecognition components. The electrochemical biosensors utilize the interaction between the target analyte and the functionalized gold nanoparticles (AuNPs) to produce an electrochemical signal, which can then be measured and quantified.[97] The methodology mentioned above exhibits a high level of sensitivity and is frequently employed in clinical diagnostics to detect glucose, cholesterol, and a range of other biomolecules. In addition, gold nanoparticles (AuNPs) have been utilized in the advancement of lateral flow assays (LFAs), a commonly employed method in point-of-care diagnostics.[98] Lateral flow assays (LFAs) are uncomplicated paper-based instruments that leverage the capillary action of a liquid to facilitate the movement of a sample across a test strip. These test strips are equipped with immobilized gold nanoparticles (AuNPs) that have been functionalized with capture molecules that are unique to the desired target. The aggregation of AuNPs is induced by the presence of the target analyte inside the sample, forming a discernible test line. Lateral flow assays (LFAs) find applications in various domains, such as pregnancy testing, infectious illness diagnosis, and environmental surveillance.[99] AuNPs have several advantageous characteristics that make them well-suited for biosensing applications within living organisms. These include their optical and electrochemical properties, as well as their biocompatibility and low toxicity. The utilization of gold nanoparticles (AuNPs) in the surveillance of biological phenomena occurring within living organisms has been investigated by researchers.[100−102] For example, introducing functionalized gold nanoparticles (AuNPs) into the circulatory system enables the selective targeting of cells or tissues.[103]

Moreover, alterations in the plasmonic characteristics of these nanoparticles offer valuable information regarding physiological mechanisms or pathological conditions.[104] The multifunctional capabilities of AuNPs are evident in their application within the field of biosensor development. Researchers can develop sensors that can detect numerous analytes simultaneously by integrating multiple layers of AuNPs with distinct functionalization. This holds significant importance in intricate diagnostic circumstances, when identifying many biomarkers is important for precise diagnosis.

Functionalizing gold nanoparticles is essential for enabling precise binding to biomolecules, which, in turn, improves the sensitivity and selectivity of biosensors. Gold nanoparticles exhibit a high surface energy and tend to agglomerate in their original form. Attaching certain molecules, such as biomolecules or ligands, to the surface of gold nanoparticles is called functionalization. This gives them unique properties that are needed for biosensing. Functionalization enables the attachment of molecules that have a strong attraction to specific biomolecules such as antibodies, aptamers, or DNA probes. These functional molecules have a recognition element that specifically binds to the target analyte. This makes sure that the biosensor only reacts to the biomolecule that it is supposed to, which cuts down on interactions that are not specific and false-positive results.[105] Attaching biomolecules to gold nanoparticles enhances the surface area for immobilization. This results in an increased loading capacity of the recognition elements, leading to a greater number of binding sites for the target analyte. The increased surface area leads to signal amplification, enhancing the sensitivity of the biosensor. The functionalized surface increases the probability of binding events, allowing for the detection of analytes, even at low concentrations. The selection of functionalization agents can influence the stability and biocompatibility of gold nanoparticles. Functional groups can enhance the stability of a biosensor in various biological settings, allowing it to maintain effectiveness in complex matrixes, such as blood, serum, or tissue samples. Biocompatible functionalization is important to keep biological molecules whole and avoid interference from interactions that are not specific to them. Functionalization enables precise adjustment of the physicochemical characteristics of gold nanoparticles, such as size, shape, and surface charge.[106] The adjustable characteristics can be fine-tuned to meet the needs of particular biosensing tasks, improving the sensor's overall efficiency. Gold-nanoparticle-based biosensors may detect numerous analytes at the same time by using various functionalization methods, allowing for multiplexed sensing. This is especially beneficial in situations where the identification of several targets is crucial for a thorough study.

Some of the field areas where gold nanoparticles are used as biosensors are mentioned below:

4.1. Forensic Science. Gold nanoparticles are widely utilized in the field of latent fingerprint formation. A novel technique has been devised by researchers wherein gold nanoparticles are deposited onto latent fingerprints.[107] The nanoparticles exhibit an affinity for the amino acids and proteins found in the perspiration and oils within fingerprint residues, augmenting the contrast and facilitating the visualization and analysis of latent prints.[108] The efficacy of this strategy has been demonstrated to be remarkably sensitive and has played a pivotal role in resolving criminal cases that are impervious to conventional approaches. Gold nanoparticles have been utilized to detect gunshot residues (GSR) on various surfaces and garments in conjunction with fingerprint analysis.[109] Gunshot residue (GSR) comprises minuscule metallic particles emitted upon a firearm's firing. The binding affinity of gold nanoparticles to metallic residues enables the targeted identification of gunshot residue (GSR) by forensic professionals, exhibiting a notable degree of sensitivity and specificity.[110] The utilization of this methodology has been of utmost significance in establishing connections between individuals under suspicion and criminal activities involving firearms, hence assuming a critical function in the realm of criminal investigations.

Another notable utilization of gold nanoparticles within forensic research pertains to the analysis of drugs.[111] Gold nanoparticles can undergo functionalization via the attachment of certain ligands or antibodies. This functionalization enables the detecting and identification of drugs and prohibited substances in diverse forensic evidence.[112] This methodology has been utilized to examine the chemical compositions of confiscated chemicals, pharmaceutical products, and biological samples such as urine and blood. Gold-nanoparticle-based assays are highly valued in drug-related forensic investigations due to their exceptional sensitivity and selectivity.

Moreover, the application of gold nanoparticles has been employed in examining minute pieces of evidence, such as hair and fibers.[113] The utilization of functionalized gold nanoparticles enables targeted binding to minute substances, augmenting their identification and analysis. This method has proven to be highly advantageous when examining minute pieces of evidence obtained from crime scenes or individuals is necessary, hence facilitating the creation of associations and corroborative evidence.

4.2. Pollution Detection. The utilization of gold nanoparticles (AuNPs) in biosensors to detect pollution is an area of study that shows great potential and is progressing rapidly. Numerous investigations have proven that nanoscale gold particles provide notable benefits in both sensitivity and selectivity. AuNP-based biosensors have been used in water quality monitoring to detect heavy metals accurately.[114] As an example, previous studies have demonstrated that sensors utilizing gold nanoparticles (AuNPs) can identify the presence of lead (Pb) in water samples at concentrations as low as 1.1 parts per billion (ppb).[115,116] Furthermore, the identification of mercury (Hg) in water has been accomplished by the utilization of gold nanoparticles (AuNPs), with documented detection thresholds as minimal as 0.02 parts per billion (ppb).[117] The results mentioned above underscore the remarkable sensitivity of biosensors utilizing gold nanoparticles (AuNPs) in the detection and evaluation of contaminants present in water.

In the area of air pollution monitoring, the incorporation of gold nanoparticles (AuNPs) into biosensors has been employed to detect volatile organic compounds (VOCs) and gases.[118] For example, a group of researchers has successfully created sensors using AuNP (gold nanoparticles) technology that can detect nitrogen dioxide (NO_2) at extremely low concentrations, namely, as low as 50 parts per billion (ppb).[119] In a study conducted by Mi et al.,[120] the detection of sulfur dioxide (SO_2) was accomplished by the utilization of sensors modified with gold nanoparticles (AuNPs). The achieved detection limits were as low as 1 ppb. The findings of this study highlight the potential of gold nanoparticles (AuNPs) in the field of air quality monitoring and the detection of hazardous contaminants.[120] Gold nanoparticle (AuNP)-based biosensors have demonstrated potential in detecting soil contaminants. Previous studies have provided evidence of their capacity to identify pesticides, such as atrazine and 2,4-dichlorophenoxyacetic acid (2,4-D), in soil samples, achieving detection limits as low as 0.5 parts per billion (ppt).[121]

Furthermore, the use of gold nanoparticles (AuNPs) has been employed in the detection of heavy metals such as cadmium (Cd) in soil, resulting in the achievement of detection limits as low as 0.1 ppm (ppm).[122] The findings underscore the multifunctionality of AuNPs in evaluating soil quality and detecting potential origins of contamination. AuNP-based biosensors have played a crucial role in detecting microbial pollution, namely, in identifying harmful bacteria present in water sources. For example, previous research has shown the identification of *Escherichia coli* (*E. coli*) in water samples through the utilization of sensors based on gold nanoparticles (AuNPs), achieving detection thresholds as low as 1 colony-forming unit per milliliter (CFU/mL).[123] In a similar vein, gold nanoparticles (AuNPs) have been utilized to detect several diseases, including Salmonella.[124] Notably, the application of AuNPs in Salmonella detection has yielded detection limits within the range of 10−100 colony-forming units per milliliter (CFU/mL).[125] The findings of this study highlight the importance of AuNP-based biosensors in accurately evaluating microbial contamination, as demonstrated by their high sensitivity and specificity.

4.3. Medical Sector. Gold nanoparticles (AuNPs) have exhibited substantial advancements in biosensors utilized in medical contexts, namely, in the sector of illness detection.[126,127] Nanoparticles possess distinctive characteristics, such as their adjustable dimensions, compatibility with biological systems, and surface chemical properties, rendering them indispensable in detecting and diagnosing diverse medical conditions.[128] An exemplary utilization pertains to identifying contagious ailments such as Human Immunodeficiency Virus (HIV). In a study conducted by Farzin et al.,[129] it was found that highly sensitive biosensors utilizing AuNP technology have been successfully produced for the detection of HIV. These biosensors have demonstrated remarkable detection limits, reaching as low as 5 femtomolar (fM). This advancement in detection capabilities has the potential to facilitate early and precise diagnosis of HIV.[129] In a similar vein, biosensors utilizing gold nanoparticle (AuNP) technology have been utilized to detect cancer biomarkers, such as prostate-specific antigen (PSA) and carcinoembryonic antigen (CEA).[130] The biosensors mentioned in the literature have exhibited remarkable sensitivity, as seen by their ability to detect analytes at extremely low concentrations in the picomolar (pM) range.[131] In addition, biosensors based on gold nanoparticles (AuNPs) have been employed to detect cardiac biomarkers, including troponin and creatine kinase-MB (CK-MB), which play a critical role in the diagnosis of heart disorders.[132] The biosensors have demonstrated remarkable sensitivity, successfully detecting troponin at concentrations as low as 1.25 picograms per milliliter (pg/mL).[133] This contribution plays a substantial role in the progression of medical diagnostics.

4.4. Food Safety. In recent years, there has been a notable surge in interest in utilizing gold nanoparticles as biosensors to ensure food safety. The distinctive optical and electrochemical characteristics these substances exhibit render them suitable contenders for the expeditious and precise identification of impurities and microorganisms in food commodities.[134,135] The utilization of gold nanoparticles in many applications, including identifying pesticides, heavy metals, and foodborne pathogens such as *Salmonella* and *E. coli*, is substantiated by comprehensive studies and reliable data.[136] The utilization of nanoparticles has several notable benefits, including a substantial surface area-to-volume ratio, the capacity to adjust their size and form, and the capability to modify their surfaces with specific biomolecules to facilitate target recognition.[137] Additionally, the interactions between the analytes and the substances under study result in alterations in optical characteristics or electrical conductivity, facilitating the ability to monitor in real-time and on-site. The use of gold nanoparticles as biosensors in food safety serves to guarantee the excellence and authenticity of food items and aid in the mitigation of foodborne diseases, rendering them a highly auspicious instrument in monitoring and regulating food safety.

4.5. Virus Detection. Gold nanoparticles have been recognized as excellent biosensors in viral detection due to their distinctive features and high level of sensitivity. The utilization of authentic data highlights the effectiveness of viral identification with a high accuracy. Researchers have achieved significant advancements in the detection of many viruses, such as HIV, influenza, and SARS-CoV-2, by employing the functionalization of gold nanoparticles with particular antibodies or aptamers that exhibit binding affinity toward viral proteins or genetic material.[138] These biosensors provide expeditious and dependable identification, frequently occurring within minutes, via alterations in color or optical signals due to the virus's existence. The high surface area to volume ratio and the ability to adjust their size make them suitable for achieving an improved binding efficiency and sensitivity. The researchers employed a technique to modify gold nanoparticles with antibodies that specifically target the hemagglutinin protein of the influenza virus.[139] This modification facilitated accurate identification and measurement of the virus in clinical samples. A recent publication in the journal *Analytical Chemistry* (DOI: 10.1021/ac2017584) presented a study that showcased the effective utilization of biosensors based on gold nanoparticles in the detection of the human immunodeficiency virus (HIV), capitalizing on the distinctive optical characteristics exhibited by these nanoparticles.[140] The speedy and visible detection was facilitated by the color shift that occurred due to the agglomeration of gold nanoparticles in the presence of the virus. The COVID-19 pandemic has brought attention to the potential of gold nanoparticle biosensors. The study presented a novel lateral flow test for SARS-CoV-2 utilizing gold nanoparticles.[141] This assay demonstrated remarkable sensitivity and specificity, yielding results within a brief time frame of less than 30 min. The instances highlight the adaptability and responsiveness of gold nanoparticles as biosensors in identifying viruses, hence presenting the potential for improved diagnostic techniques and monitoring in infectious disease control.

4.6. Neuroscience Research. Gold nanoparticles have been widely utilized as biosensors in neuroscience research, demonstrating significant scientific evidence substantiating their efficacy. The detection of the neurotransmitter dopamine with great sensitivity and selectivity was achieved through the functionalization of gold nanoparticles with aptamers.[142] This methodology facilitated the continuous monitoring of dopamine changes within the cerebral regions of live rats, hence yielding significant contributions to neurochemistry. Furthermore, a study by the authors applied electrochemical biosensors utilizing gold nanoparticles to identify amyloid-beta peptides, which are significant biomarkers associated with Alzheimer's disease.[143] The biosensors demonstrated remarkable sensitivity, enabling the timely identification of amyloid-beta aggregation, a characteristic disease feature. Many other studies underscore the capacity of gold nanoparticle biosensors to provide accurate and instantaneous quantification of neurotransmitters and biomarkers. This capability has contributed to significant advancements in our comprehension of neurobiology and holds promise for the development of diagnostic instruments for neurological illnesses.

5. FUTURE PERSPECTIVE

Gold nanoparticles have emerged as a captivating and versatile biosensor platform, offering remarkable promise for advanced applications in the not-so-distant future. These nanoscale gold particles possess unique properties that make them ideal candidates for biosensing. Their tunable size, shape, and surface properties allow for precise control over their interactions with biomolecules, enabling the sensitive and selective detection of a wide range of analytes. Furthermore, gold nanoparticles exhibit localized surface plasmon resonance (LSPR), which causes them to absorb and scatter light at specific wavelengths depending on their size and shape. This attribute can be harnessed for the label-free and real-time detection of biomolecular interactions, making them particularly appealing for diagnostics, environmental monitoring, and drug development.

The future of gold nanoparticles as biosensors holds several exciting prospects. As nanotechnology and materials science advances, we can expect even more tailored gold nanoparticles with enhanced stability, biocompatibility, and functionality. Researchers are exploring multifunctional nanoparticles that can detect and deliver therapeutic agents to target cells, thereby revolutionizing drug delivery systems. Moreover, integration with microfluidic devices and lab-on-a-chip technologies will facilitate point-of-care testing and remote monitoring, transforming healthcare accessibility. Gold nanoparticles as biosensors are poised to play a pivotal role in understanding complex biological processes, identifying diseases at earlier stages, and monitoring treatment efficacy. The future is bright for these tiny, shimmering particles, which are set to usher in a new era of precision and personalized medicine, environmental protection, and quality control in various industries.

■ CONCLUSION

In conclusion, the field of nanotechnology has experienced rapid growth and diversification, ushering in a new era of scientific exploration with far-reaching implications. As a multidisciplinary subdomain, nanobiotechnology epitomizes this amalgamation of sciences and technologies to produce nano-objects with profound applications. In nanomaterials, nanoparticles, particularly gold nanoparticles (GNPs), have taken center stage due to their remarkable properties and versatility. The fascination with GNPs stems from their unique characteristics, which transcend various shapes and sizes. These attributes are instrumental in defining their distinct chemical, physical, and optical properties, which sets them apart from bulk materials. GNPs have been widely explored for many applications, from advanced chemical detection to catalysis and optoelectronics. Furthermore, their exceptional antibacterial properties are especially relevant to the growing antibiotic resistance issues. The important key feature of gold nanoparticles is localized surface plasmon resonance (LSPR) which allows for label-free, real-time monitoring of biomolecular interactions, providing great sensitivity for detecting low analyte concentrations. Increased surface area improves the immobilization of biomolecules, resulting in signal amplification and enhanced detection limits. This role of gold nanoparticles would be a future need for biosensors, as it is essential for instruments in medical diagnostics, environmental monitoring, and bioanalytical research due to their properties.

With its rich history in medicine, gold has found application in various forms, including treating medical conditions. The synthesis of GNPs is a pivotal step in harnessing their potential, and researchers have employed various biological agents and methods to facilitate this synthesis. Extracellular synthesis has emerged as an efficient and promising avenue, streamlining the process. Nanoparticle synthesis methods can be broadly categorized into “top-bottom” and “bottom-top” approaches, each with its advantages and limitations. Traditional manufacturing methods often involve toxic substances that pose environmental and biological risks. Consequently, the field is shifting toward more sustainable and safer approaches.

In the realm of biosensors, nanotechnology has given rise to highly sensitive and selective devices for the detection of biological molecules. GNPs have garnered significant attention among various nanomaterials due to their unique properties. This article has delved into the world of GNPs as biosensors, shedding light on their characteristics, applications, and the driving forces behind their popularity in diagnostics. It underscores the potential for GNPs to revolutionize various scientific domains and highlights the innovative biosynthesis methods that promise future advancements. Overall, nanotechnology, particularly gold nanoparticles, continues to drive scientific research and technological innovation, paving the way for transformative applications across various disciplines.

■ ASSOCIATED CONTENT

Data Availability Statement

No data was used for the research described in the article.

■ AUTHOR INFORMATION

Corresponding Authors

Arun Karnwal — *School of Bioengineering & Biosciences, Lovely Professional University, Phagwara 144411 Punjab, India*; Email: arunkarnwal@gmail.com

Kaizar Hossain — *Department of Environmental Science, Asutosh College, University of Calcutta, Kolkata 700026 West Bengal, India*; orcid.org/0000-0002-3903-6161; Email: kaizar.kaizar@gmail.com

Gaurav Pant — *Department of Microbiology, Graphic Era (Deemed to be University), Dehradun 248009 Uttarakhand, India*; Email: rgauravpant@gmail.com

Authors

Rohan Samir Kumar Sachan — *School of Bioengineering & Biosciences, Lovely Professional University, Phagwara 144411 Punjab, India*

Inderpal Devgon — *School of Bioengineering & Biosciences, Lovely Professional University, Phagwara 144411 Punjab, India*

Jyotsna Devgon — *Centre for Interdisciplinary Biomedical Research, Adesh University, Bathinda 151101 Punjab, India*

Mitali Panchpuri — *School of Pharmaceutical and Population Health Informatics, DIT University, Dehradun 248009 Uttarakhand, India*

Akil Ahmad — *Department of Chemistry, College of Science and Humanities in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia*; orcid.org/0000-0003-4912-287X

Mohammed B. Alshammari — *Department of Chemistry, College of Science and Humanities in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia*

Gaurav Kumar — *School of Bioengineering & Biosciences, Lovely Professional University, Phagwara 144411 Punjab, India*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c10352

Funding

No funds or grants were received.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

All authors are highly thankful to Prince Sattam bin Abdulaziz University for their support and encouragement. This study is supported via funding from Prince Sattam bin Abdulaziz University project number (PSAU/2024/R/1445). The authors also thank the Lovely Professional University, Phagwara, India, Adesh University, Bathinda, Punjab, India, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India, DIT University, Dehradun, Uttarakhand, India and Asutosh College, Kolkata, West Bengal, India for technical support in completing this study.

■ REFERENCES

(1) Wang, H.; Zhang, W.; Ladika, D.; Yu, H.; Gailevičius, D.; Wang, H.; et al. Two-Photon Polymerization Lithography for Optics and Photonics: Fundamentals, Materials, Technologies, and Applications. *Adv. Funct Mater.* **2023**, *33*, 2214211.

(2) Tomás, H.; Rodrigues, J. Dendrimers and dendrimer-based nano-objects for oncology applications. *New Trends in Smart Nanostructured Biomaterials in Health Sciences* **2023**, 41−78.

(3) Joudeh, N.; Linke, D. Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *Journal of Nanobiotechnology.* **2022**, *20* (1), 262.

(4) Zein, R.; Sharrouf, W.; Selting, K. Physical properties of nanoparticles that result in improved cancer targeting. *Journal of Oncology.* **2020**, *2020*, 194780.

(5) Bansal, S. A.; Kumar, V.; Karimi, J.; Singh, A. P.; Kumar, S. Role of gold nanoparticles in advanced biomedical applications. *Nanoscale Advances.* **2020**, *2* (9), 3764−87.

(6) Adeyemi, J. O.; Fawole, O. A. Metal-Based Nanoparticles in Food Packaging and Coating Technologies: A Review. *Biomolecules 2023, Vol 13, Page 1092* **2023**, *13*, 1092.

(7) Das, S.; Sen, B.; Debnath, N. Recent trends in nanomaterials applications in environmental monitoring and remediation. *Environmental Science and Pollution Research* **2015**, *22*, 18333−44.

(8) Shedbalkar, U.; Singh, R.; Wadhwani, S.; Gaidhani, S.; Chopade, B. A. Microbial synthesis of gold nanoparticles: Current status and future prospects. *Adv. Colloid Interface Sci.* **2014**, *209*, 40−8.

(9) Pandit, C.; Roy, A.; Ghotekar, S.; Khusro, A.; Islam, M. N.; Emran, T. B.; Lam, S. E.; Khandaker, M. U.; Bradley, D. A. Biological agents for synthesis of nanoparticles and their applications. *Journal of King Saud University-Science.* **2022**, *34* (3), 101869.

(10) Yadi, M.; Mostafavi, E.; Saleh, B.; Davaran, S.; Aliyeva, I.; Khalilov, R.; et al. Current developments in green synthesis of metallic nanoparticles using plant extracts: a review. *Artif Cells Nanomed Biotechnol* **2018**, *46*, 336−43.

(11) Farirai, F.; Ozonoh, M.; Aniokete, T. C.; Eterigho-Ikelegbe, O.; Mupa, M.; Zeyi, B.; et al. Methods of extracting silica and silicon from agricultural waste ashes and application of the produced silicon in solar cells: a mini-review. *International Journal of Sustainable Engineering* **2021**, *14*, 57−78.

(12) Bhardwaj, H.; Sumana, G.; Marquette, C. A. A label-free ultrasensitive microfluidic surface Plasmon resonance biosensor for Aflatoxin B1 detection using nanoparticles integrated gold chip. *Food Chem.* **2020**, *307*, 125530.

(13) Hammami, I.; Alabdallah, N. M. Gold nanoparticles: Synthesis properties and applications. *Journal of king Saud university-science.* **2021**, *33* (7), 101560.

(14) Mihaylov, M.; Knözinger, H.; Hadjiivanov, K.; Gates, B. C. Characterization of the Oxidation States of Supported Gold Species by IR Spectroscopy of Adsorbed CO. *Chemie Ingenieur Technik* **2007**, *79*, 795−806.

(15) Muraca, F.; Boselli, L.; Castagnola, V.; Dawson, K. A. Ultrasmall gold nanoparticle cellular uptake: influence of transient bionano interactions. *ACS Applied Bio Materials.* **2020**, 3 (6), 3800−8.

(16) Wang, Y.; Muratore, M. E.; Echavarren, A. M. Gold Carbene or Carbenoid: Is There a Difference? *Chemistry − A European Journal* **2015**, *21*, 7332−9.

(17) Langille, M. R.; Personick, M. L.; Zhang, J.; Mirkin, C. A. Defining rules for the shape evolution of gold nanoparticles. *J. Am. Chem. Soc.* **2012**, *134*, 14542−54.

(18) González-Gallardo, S.; Bollermann, T.; Fischer, R. A.; Murugavel, R. Cyclopentadiene based low-valent group 13 metal compounds: Ligands in coordination chemistry and link between metal rich molecules and intermetallic materials. *Chem. Rev.* **2012**, *112*, 3136−70.

(19) Schwerdtfeger, P.; Hermann, H. L.; Schmidbaur, H. Stability of the gold(I)-phosphine bond. A comparison with other group 11 elements. *Inorg. Chem.* **2003**, *42*, 1334−42.

(20) Liu, X.; Li, Y.; Zeng, L.; Li, X.; Chen, N.; Bai, S.; et al. A Review on Mechanochemistry: Approaching Advanced Energy Materials with Greener Force. *Adv. Mater.* **2022**, *34*, 2108327.

(21) Liu, Y.; Ai, K.; Lu, L. Polydopamine and its derivative materials: Synthesis and promising applications in energy, environmental, and biomedical fields. *Chem. Rev.* **2014**, *114*, 5057−115.

(22) Alzahrani, A. R.; Ibrahim, I. A. A.; Shahzad, N.; Shahid, I.; Alanazi, I. M.; Falemban, A. H.; et al. An application of carbohydrate polymers-based surface-modified gold nanoparticles for improved target delivery to liver cancer therapy - A systemic review. *Int. J. Biol. Macromol.* **2023**, *253*, 126889.

(23) Mirza, A. U.; Kareem, A. Metal oxide-based photocatalyst for the degradation of organic pollutants in water, 2019.

(24) Mahmood Ansari, S.; Saquib, Q.; De Matteis, V.; Awad Alwathnani, H.; Ali Alharbi, S.; Ali Al-Khedhairy, A. Marine Macroalgae Display Bioreductant Efficacy for Fabricating Metallic Nanoparticles: Intra/Extracellular Mechanism and Potential Biomedical Applications. *Bioinorg Chem. Appl.* **2021**, *2021*, 985377.

(25) Malik, P.; Shankar, R.; Malik, V.; Sharma, N.; Mukherjee, T. K. Green Chemistry Based Benign Routes for Nanoparticle Synthesis. *Journal of Nanoparticles* **2014**, *2014*, 302429.

(26) Kumar, P.; Debele, S. E.; Sahani, J.; Rawat, N.; Marti-Cardona, B.; Alfieri, S. M.; et al. Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. *Science of The Total Environment* **2021**, *784*, 147058.

(27) Shankar, S. S.; Rai, A.; Ahmad, A.; Sastry, M. Rapid synthesis of Au, Ag, and bimetallic Au core-Ag shell nanoparticles using Neem (Azadirachta indica) leaf broth. *J. Colloid Interface Sci.* **2004**, *275*, 496−502.

(28) Tippayawat, P.; Phromviyo, N.; Boueroy, P.; Chompoosor, A. Green synthesis of silver nanoparticles in aloe vera plant extract prepared by a hydrothermal method and their synergistic antibacterial activity. *PeerJ.* **2016**, *4*, e2589.

(29) Amina, S. J.; Guo, B. A Review on the Synthesis and Functionalization of Gold Nanoparticles as a Drug Delivery Vehicle. *Int. J. Nanomedicine* **2020**, *15*, 9823.

(30) Song, J. Y.; Kwon, E. Y.; Kim, B. S. Biological synthesis of platinum nanoparticles using Diopyros kaki leaf extract. *Bioprocess Biosyst Eng.* **2010**, *33*, 159−64.

(31) Zhang, D.; Ma, X. L.; Gu, Y.; Huang, H.; Zhang, G. W. Green Synthesis of Metallic Nanoparticles and Their Potential Applications to Treat Cancer. *Front Chem.* **2020**, *8*, 8.

(32) Huang, J.; Zhu, Y.; Yang, X.; Chen, W.; Zhou, Y.; Li, C. Flexible 3D porous CuO nanowire arrays for enzymeless glucose sensing: in situ engineered versus ex situ piled. *Nanoscale* **2015**, *7*, 559−69.

(33) Ankamwar, B.; Damle, C.; Ahmad, A.; Sastry, M. Biosynthesis of gold and silver nanoparticles using Emblica Officinalis fruit extract, their phase transfer and transmetallation in an organic solution. *J. Nanosci Nanotechnol* **2005**, *5*, 1665−71.

(34) Huang, J.; Li, Q.; Sun, D.; Lu, Y.; Su, Y.; Yang, X.; et al. Biosynthesis of silver and gold nanoparticles by novel sundried Cinnamomum camphora leaf. *Nanotechnology* **2007**, *18*, 105104.

(35) Kalimuthu, K.; Cha, B. S.; Kim, S.; Park, K. S. Eco-friendly synthesis and biomedical applications of gold nanoparticles: A review. *Microchemical Journal* **2020**, *152*, 104296.

(36) Luangpipat, T.; Beattie, I. R.; Chisti, Y.; Haverkamp, R. G. Gold nanoparticles produced in a microalga. *J. Nanopart. Res.* **2011**, *13*, 6439−45.

(37) Lengke, M. F.; Sanpawanitchakit, C.; Southam, G. Biosynthesis of Gold Nanoparticles: A Review. *Metal Nanoparticles in Microbiology* **2011**, 37−74.

(38) Hammami, I.; Alabdallah, N. M.; jomaa, A Al; kamoun, M. Gold nanoparticles: Synthesis properties and applications. *J. King Saud Univ Sci.* **2021**, *33*, 101560.

(39) Arockiya Aarthi Rajathi, F.; Parthiban, C.; Ganesh Kumar, V.; Anantharaman, P. Biosynthesis of antibacterial gold nanoparticles using brown alga, Stoechospermum marginatum (kützing). *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.* **2012**, *99*, 166−73.

(40) Abdel-Raouf, N.; Al-Enazi, N. M.; Ibraheem, I. B. M. Green biosynthesis of gold nanoparticles using Galaxaura elongata and characterization of their antibacterial activity. *Arabian Journal of Chemistry* **2017**, *10*, S3029−39.

(41) Alghuthaymi, M. A.; Almoammar, H.; Rai, M.; Said-Galiev, E.; Abd-Elsalam, K. A. Myconanoparticles: synthesis and their role in phytopathogens management. *Biotechnol Biotechnol Equip* **2015**, *29*, 221.

(42) Shankar, P. D.; Shobana, S.; Karuppusamy, I.; Pugazhendhi, A.; Ramkumar, V. S.; Arvindnarayan, S.; et al. A review on the biosynthesis of metallic nanoparticles (gold and silver) using bio-components of microalgae: Formation mechanism and applications. *Enzyme Microb Technol.* **2016**, *95*, 28−44.

(43) Khan, A. U.; Khan, M.; Malik, N.; Cho, M. H.; Khan, M. M. Recent progress of algae and blue−green algae-assisted synthesis of gold nanoparticles for various applications. *Bioprocess Biosyst Eng.* **2019**, *42*, 1−15.

(44) Costa, L. H.; Hemmer, J. V.; Wanderlind, E. H.; Gerlach, O. M. S.; Santos, A. L. H.; Tamanaha, M. S.; et al. Green Synthesis of Gold Nanoparticles Obtained from Algae Sargassum cymosum: Optimization, Characterization and Stability. *Bionanoscience* **2020**, *10*, 1049−62.

(45) Pal, G.; Rai, P.; Pandey, A. Green synthesis of nanoparticles: A greener approach for a cleaner future. *Green Synthesis, Characterization and Applications of Nanoparticles* **2019**, 1−26.

(46) Gurunathan, B.; Bathrinarayanan, P. V.; Muthukumarasamy, V. K.; Thangavelu, D. Characterization of intracellular gold nanoparticles synthesized by biomass of aspergillus terreus. *Acta Metallurgica Sinica (English Letters)* **2014**, *27*, 569−72.

(47) Ahmad, A.; Senapati, S.; Khan, M. I.; Kumar, R.; Sastry, M. Extracellular biosynthesis of monodisperse gold nanoparticles by a novel extremophilic actinomycete, thermomonospora sp. *Langmuir* **2003**, *19*, 3550−3.

(48) Garg, A.; Sharma, G. S.; Goyal, A. K.; Ghosh, G.; Si, S. C.; Rath, G. Recent advances in topical carriers of anti-fungal agents. *Heliyon* **2020**, *6*, No. e04663.

(49) Slavin, Y. N.; Bach, H. Mechanisms of Antifungal Properties of Metal Nanoparticles. *Nanomaterials* **2022**, *12*, 4470.

(50) Loshchinina, E. A.; Vetchinkina, E. P.; Kupryashina, M. A. Diversity of Biogenic Nanoparticles Obtained by the Fungi-Mediated Synthesis: A Review. *Biomimetics* **2023**, *8*, 1.

(51) Owaid, M. N.; Rabeea, M. A.; Abdul Aziz, A.; Jameel, M. S.; Dheyab, M. A. Mushroom-assisted synthesis of triangle gold nanoparticles using the aqueous extract of fresh Lentinula edodes (shiitake), Omphalotaceae. *Environ. Nanotechnol Monit Manag* **2019**, *12*, 100270.

(52) Smaoui, S.; Chérif, I.; Ben Hlima, H.; Khan, M. U.; Rebezov, M.; Thiruvengadam, M.; et al. Zinc oxide nanoparticles in meat packaging: A systematic review of recent literature. *Food Packag Shelf Life* **2023**, *36*, 101045.

(53) Carrière, M.; Henrique, M.; Buzzetti, P.; Gorgy, K.; Giroud, F.; Li, H.; Borsali, R.; et al. Nanostructured electrodes based on multiwalled carbon nanotube/glyconanoparticles for the specific immobilization of bilirubin oxidase: Application to the electrocatalytic O2 reduction. *Bioelectrochemistry* **2023**, *150*, 108328.

(54) Mishra, A.; Tripathy, S. K.; Wahab, R.; Jeong, S. H.; Hwang, I.; Yang, Y. B.; et al. Microbial synthesis of gold nanoparticles using the fungus Penicillium brevicompactum and their cytotoxic effects against mouse mayo blast cancer C 2C 12 cells. *Appl. Microbiol. Biotechnol.* **2011**, *92*, 617−30.

(55) Xu, P.; Zeng, G.; Huang, D.; Hu, S.; Feng, C.; Lai, C.; et al. Synthesis of iron oxide nanoparticles and their application in Phanerochaete chrysosporium immobilization for Pb(II) removal. *Colloids Surf. A Physicochem Eng. Asp* **2013**, *419*, 147−55.

(56) Bamburowicz-Klimkowska, M.; Poplawska, M.; Grudzinski, I. P. Nanocomposites as biomolecules delivery agents in nanomedicine. *Journal of Nanobiotechnology 2019 17:1* **2019**, *17*, 1−32.

(57) Bhardwaj, K.; Sharma, A.; Tejwan, N.; Bhardwaj, S.; Bhardwaj, P.; Nepovimova, E.; et al. Pleurotus Macrofungi-Assisted Nanoparticle Synthesis and Its Potential Applications: A Review. *Journal of Fungi* **2020**, *6*, 351.

(58) Hulkoti, N. I.; Taranath, T. C. Biosynthesis of nanoparticles using microbes—A review. *Colloids Surf. B Biointerfaces* **2014**, *121*, 474−83.

(59) Roy, A.; Pandit, C.; Gacem, A.; Alqahtani, M. S.; Bilal, M.; Islam, S.; et al. Biologically Derived Gold Nanoparticles and Their Applications. *Bioinorg Chem. Appl.* **2022**, *2022*, 8184217.

(60) Hetta, H. F.; Al-Kadmy, I. M. S.; Khazaal, S. S.; Abbas, S.; Suhail, A.; El-Mokhtar, M. A.; et al. Antibiofilm and antivirulence potential of silver nanoparticles against multidrug-resistant Acinetobacter baumannii. *Sci. Rep* **2021**, *11*, 10751.

(61) Naseer, A.; Ali, A.; Ali, S.; Mahmood, A.; Kusuma, H. S.; Nazir, A.; et al. Biogenic and eco-benign synthesis of platinum nanoparticles (Pt NPs) using plants aqueous extracts and biological derivatives: environmental, biological and catalytic applications. *Journal of Materials Research and Technology* **2020**, *9*, 9093−107.

(62) Sánchez-López, E.; Gomes, D.; Esteruelas, G.; Bonilla, L.; Lopez-Machado, A. L.; Galindo, R.; et al. Metal-Based Nanoparticles as Antimicrobial Agents: An Overview. *Nanomaterials* **2020**, *10*, 292.

(63) Yoha, K. S.; Nida, S.; Dutta, S.; Moses, J. A.; Anandharamakrishnan, C. Targeted Delivery of Probiotics: Perspectives on Research and Commercialization. *Probiotics Antimicrob Proteins* **2022**, *14*, 15.

(64) Yoha, K. S.; Nida, S.; Dutta, S.; Moses, J. A.; Anandharamakrishnan, C. Targeted Delivery of Probiotics: Perspectives on Research and Commercialization. *Probiotics Antimicrob Proteins* **2022**, *14*, 15.

(65) Thammawithan, S.; Talodthaisong, C.; Srichaiyapol, O.; Patramanon, R.; Hutchison, J. A.; Kulchat, S. Andrographolide stabilized-silver nanoparticles overcome ceftazidime-resistant Burkholderia pseudomallei: study of antimicrobial activity and mode of action. *Sci. Rep* **2022**, *12*, 10701.

(66) Vizzini, P.; Braidot, M.; Vidic, J.; Manzano, M. Electrochemical and Optical Biosensors for the Detection of Campylobacter and Listeria: An Update Look. *Micromachines (Basel)* **2019**, *10*, 500.

(67) Malhotra, M.; Sood, S.; Mukherjee, A.; Muralidhar, S.; Bala, M. Genital Chlamydia trachomatis: An update. *Indian J. Med. Res.* **2013**, *138*, 303.

(68) Liberato, V.; Benevenuti, C.; Coelho, F.; Botelho, A.; Amaral, P.; Pereira, N.; et al. Clostridium sp. *as Bio-Catalyst for Fuels and Chemicals Production in a Biorefinery Context. Catalysts 2019, Vol 9, Page 962* **2019**, *9*, 962.

(69) Becker, J.; Rohles, C. M.; Wittmann, C. Metabolically engineered Corynebacterium glutamicum for bio-based production of chemicals, fuels, materials, and healthcare products. *Metab Eng.* **2018**, *50*, 122−41.

(70) Gebreslassie, Y. T.; Gebremeskel, F. G. Green and cost-effective biofabrication of copper oxide nanoparticles: Exploring antimicrobial and anticancer applications. *Biotechnology Reports* **2024**, *41*, No. e00828.

(71) Bindschedler, S.; Cailleau, G.; Verrecchia, E.; Benzerara, K.; Miot, J.; Coradin, T. Role of Fungi in the Biomineralization of Calcite. *Minerals 2016, Vol 6, Page 41* **2016**, *6*, 41.

(72) Cai, F.; Li, S.; Huang, H.; Iqbal, J.; Wang, C.; Jiang, X. Green synthesis of gold nanoparticles for immune response regulation: Mechanisms, applications, and perspectives. *J. Biomed Mater. Res. A* **2022**, *110*, 424−42.

(73) Ali, M. R.; Bacchu, M. S.; Setu, M. A. A.; Akter, S.; Hasan, M. N.; Chowdhury, F. T.; et al. Development of an advanced DNA biosensor for pathogenic Vibrio cholerae detection in real sample. *Biosens Bioelectron* **2021**, *188*, 113338.

(74) Zhang, J.; Wanner, J.; Singh, O. V. Extremophiles and Biosynthesis of Nanoparticles. *Bio-Nanoparticles: Biosynthesis and Sustainable Biotechnological Implications* **2015**, 101−21.

(75) Cudalbeanu, M.; Peitinho, D.; Silva, F.; Marques, R.; Pinheiro, T.; Ferreira, A. C.; Marques, F.; Paulo, A.; Soeiro, C. F.; Sousa, S. A.; Leitão, J. H. Sono-biosynthesis and characterization of AuNPs from Danube Delta Nymphaea alba root extracts and their biological properties. *Nanomaterials.* **2021**, *11* (6), 1562.

(76) Narayanan, K. B.; Sakthivel, N. Biological synthesis of metal nanoparticles by microbes. *Adv. Colloid Interface Sci.* **2010**, *156*, 1−13.

(77) Sayadi, K.; Akbarzadeh, F.; Pourmardan, V.; Saravani-Aval, M.; Sayadi, J.; Pal, N.; et al. Methods of green synthesis of Au NCs with emphasis on their morphology: A mini-review. *Heliyon* **2021**, *7*, No. e07250.

(78) Mohanta, Y. K.; Hashem, A.; Abd_Allah, E. F.; Jena, S. K.; Mohanta, T. K. Bacterial synthesized metal and metal salt nanoparticles in biomedical applications: An up and coming approach. *Appl. Organomet. Chem.* **2020**, *34*, No. e5810.

(79) Jain, P. K.; Huang, X.; El-Sayed, I. H.; El-Sayed, M. A. Review of some interesting surface plasmon resonance-enhanced properties of noble metal nanoparticles and their applications to biosystems. *Plasmonics* **2007**, *2*, 107−18.

(80) Khan, A. K.; Rashid, R.; Murtaza, G.; Zahra, A. Gold Nanoparticles: Synthesis and Applications in Drug Delivery. *Tropical Journal of Pharmaceutical Research* **2014**, *13*, 1169−77.

(81) Seku, K.; Hussaini, S. S.; Radhakrishna Reddy, M.; Bhagavanth Reddy, G.; Kishore Kumar, K. Fungal-mediated synthesis of gold nanoparticles and their biological applications. *Fungal Cell Factories for Sustainable Nanomaterials Production and Agricultural Applications* **2023**, 23−58.

(82) Nejati, K.; Dadashpour, M.; Gharibi, T.; Mellatyar, H.; Akbarzadeh, A. Biomedical Applications of Functionalized Gold Nanoparticles: A Review. *Journal of Cluster Science 2021 33:1* **2022**, *33*, 1−16.

(83) Xu, R.; Ouyang, L.; Chen, H.; Zhang, G.; Zhe, J. Recent advances in biomolecular detection based on aptamers and nanoparticles. *Biosensors.* **2023**, *13* (4), 474.

(84) Al-Bataineh, Q. M.; Telfah, A. D.; Tavares, C. J.; Hergenröder, R. Surface plasmon coupling between wide-field SPR microscopy and gold nanoparticles. *Scientific Reports.* **2023**, *13* (1), 22405.

(85) Aldewachi, H.; Chalati, T.; Woodroofe, M. N.; Bricklebank, N.; Sharrack, B.; Gardiner, P. Gold nanoparticle-based colorimetric biosensors. *Nanoscale* **2018**, *10*, 18−33.

(86) Unser, S.; Bruzas, I.; He, J.; Sagle, L. Localized Surface Plasmon Resonance Biosensing: Current Challenges and Approaches. *Sensors* **2015**, *15*, 15684−716.

(87) Cordeiro, M.; Carlos, F. F.; Pedrosa, P.; Lopez, A.; Baptista, P. V. Gold Nanoparticles for Diagnostics: Advances towards Points of Care. *Diagnostics* **2016**, *6*, 43.

(88) Oliverio, M.; Perotto, S.; Messina, G. C.; Lovato, L.; De Angelis, F. Chemical Functionalization of Plasmonic Surface Biosensors: A Tutorial Review on Issues, Strategies, and Costs. *ACS Appl. Mater. Interfaces* **2017**, *9*, 29394−411.

(89) Semwal, V.; Jensen, O. R.; Bang, O.; Janting, J. Investigation of Performance Parameters of Spherical Gold Nanoparticles in Localized Surface Plasmon Resonance Biosensing. *Micromachines.* **2023**, *14* (9), 1717.

(90) Nguyen, Q. K.; Duong, M. N.; Nguyen, T. B.; Pham, T. N. M. Visual detection and highly sensitive quantification of antibiotic Meropenem in pharmaceutical and human plasma samples using gold nanoparticles. *Sep. Sci. Technol.* **2023**, *58*, 1540−51.

(91) Jin, C.; Wu, Z.; Molinski, J. H.; Zhou, J.; Ren, Y.; Zhang, J. X. J. Plasmonic nanosensors for point-of-care biomarker detection. *Mater. Today Bio* **2022**, *14*, 100263.

(92) Khan, S.; Hasan, A.; Attar, F.; Sharifi, M.; Siddique, R.; Mraiche, F.; et al. Gold Nanoparticle-Based Platforms for Diagnosis and Treatment of Myocardial Infarction. *ACS Biomater Sci. Eng.* **2020**, *6*, 6460−77.

(93) Mukama, O.; Wu, W.; Wu, J.; Lu, X.; Liu, Y.; Liu, Y.; et al. A highly sensitive and specific lateral flow aptasensor for the detection of human osteopontin. *Talanta* **2020**, *210*, 120624.

(94) Dadmehr, M.; Mortezaei, M.; Korouzhdehi, B. Dual mode fluorometric and colorimetric detection of matrix metalloproteinase MMP-9 as a cancer biomarker based on AuNPs@gelatin/AuNCs nanocomposite. *Biosens Bioelectron* **2023**, *220*, 114889.

(95) Hosseini, S. A.; Kardani, A.; Yaghoobi, H. A comprehensive review of cancer therapies mediated by conjugated gold nanoparticles with nucleic acid. *International Journal of Biological Macromolecules.* **2023**, *253*, 127184.

(96) Dutta, S. DNA functionalized gold and silver nanoparticles. *Gold and Silver Nanoparticles: Synthesis and Applications* **2023**, 411−34.

(97) Beck, F.; Horn, C.; Baeumner, A. J. Ag nanoparticles outperform Au nanoparticles for the use as label in electrochemical point-of-care sensors. *Analytical and Bioanalytical Chemistry.* **2022**, *414*, 475.

(98) Gold nanoparticles (AuNPs) have been utilized in the advancement of lateral flow assays (LFAs), a commonly employed method in point-of-care diagnostics.

(99) Dey, M. K.; Iftesum, M.; Devireddy, R.; Gartia, M. R. New technologies and reagents in lateral flow assay (LFA) designs for enhancing accuracy and sensitivity. *Analytical Methods* **2023**, *15*, 4351−76.

(100) Alishah Aratboni, H.; Rafiei, N.; Mehdizadeh Allaf, M.; Abedini, S.; Naseema Rasheed, R.; Seif, A.; et al. Nanotechnology: An outstanding tool for increasing and better exploitation of microalgae valuable compounds. *Algal Res.* **2023**, *71*, 103019.

(101) Tan, K. F.; In, L. L. A.; Vijayaraj Kumar, P. Surface Functionalization of Gold Nanoparticles for Targeting the Tumor Microenvironment to Improve Antitumor Efficiency. *ACS Appl. Bio Mater.* **2023**, *6*, 2944−81.

(102) Manjubaashini, N.; Daniel Thangadurai, T. Unaided-eye detection of diverse metal ions by AuNPs-based nanocomposites: A review. *Microchemical Journal* **2023**, *190*, 108628.

(103) Didamson, O. C.; Chandran, R.; Abrahamse, H. A Gold Nanoparticle Bioconjugate Delivery System for Active Targeted Photodynamic Therapy of Cancer and Cancer Stem Cells. *Cancers (Basel)* **2022**, *14*, 4558.

(104) Lin, J. S.; Tian, X. D.; Li, G.; Zhang, F. L.; Wang, Y.; Li, J. F. Advanced plasmonic technologies for multi-scale biomedical imaging. *Chem. Soc. Rev.* **2022**, *51*, 9445−68.

(105) Priecel, P.; Salami, H. A.; Padilla, R. H.; Zhong, Z.; Lopez-Sanchez, J. A. Anisotropic gold nanoparticles: Preparation and applications in catalysis. *Chinese Journal of Catalysis* **2016**, *37*, 1619−50.

(106) Amina, S. J.; Guo, B. A review on the synthesis and functionalization of gold nanoparticles as a drug delivery vehicle. *Int. J. Nanomedicine* **2020**, *15*, 9823−57.

(107) Rao, S. Emerging Latent Fingerprint Imaging Technologies (Instrumental Methods)-A Review of Recent Literature. *Forensic, Legal & Investigative Sciences* **2022**, *8*, 1−6.

(108) Sharma, V.; Choudhary, S.; Mankotia, P.; Kumari, A.; Sharma, K.; Sehgal, R.; et al. Nanoparticles as fingermark sensors. *TrAC Trends in Analytical Chemistry* **2021**, *143*, 116378.

(109) Anand, V. R.; Waghmare, N. P.; Joshi, M.; Tiwari, N. An experimental investigation of gunshot residue (GSR) evidence: Directly from targeted fabric using sem. *International Journal of Medical Toxicology & Legal Medicine.* **2020**, *23* (3and4), 233−44.

(110) Muehlethaler, C. Raman and Surface-Enhanced Raman Scattering (SERS) for Trace Analysis. *Leading Edge Techniques in Forensic Trace Evidence Analysis: More New Trace Analysis Methods* **2022**, 309−37.

(111) Hassan, S. M.; Malik, A. A.; Shehzad, H. H. New Perspective of Calcium Oxide Nanoparticles in Forensic Science. *International Journal for Electronic Crime Investigation* **2022**, *6*, 16−16.

(112) Singh, H.; Parmar, S.; Khisse, D.; Mazumdar, S.; Jasani, S.; Sharma, A.; et al. Functionalization of Nanomaterials for Fingerprinting. *Materials Horizons: From Nature to Nanomaterials* **2023**, *Part F1301*, 17−38.

(113) Ali, B. S. The Application of nanotechnology in criminology and forensic Sciences. *International Journal for Electronic Crime Investigation* **2023**, *6*, 13−8.

(114) Satpute, N.; Shrivas, K.; Dewangan, K. Smart Nanosensors for Pesticides and Heavy Metals Detection. *Nanorobotics and Nanodiagnostics in Integrative Biology and Biomedicine* **2023**, 433−52.

(115) Shrivastava, P.; Jain, V. K.; Nagpal, S. Nanoparticle intervention for heavy metal detection: A review. *Environ. Nanotechnol Monit Manag* **2022**, *17*, 100667.

(116) Bansal, A.; Samir, R.; Sachan, K.; Devgon, J.; Devgon, I.; Karnwal, A. Nanotechnology in Environmental Clean-up. *Materials Research Proceedings* **2023**, *145*, 281−310.

(117) Singh, G.; Nisha; Kumar, A.; Prasher, P.; Mudila, H. Assessment of toxicity and electrochemical sensing of arsenic in aqueous sources. *Https://DoiOrg/101680/Jenes2200011* **2023**, *18*, 10−23.

(118) Gan, Z.; Zhou, Q.; Zheng, C.; Wang, J. Challenges and applications of volatile organic compounds monitoring technology in plant disease diagnosis. *Biosens Bioelectron* **2023**, *237*, 115540.

(119) Heo, J. H.; Sung, M.; Trung, T. Q.; Lee, Y.; Jung, D. H.; Kim, H.; et al. Sensor design strategy for environmental and biological monitoring. *EcoMat* **2023**, *5*, No. e12332.

(120) Mi, K.; Tong, L.; Yu, M.; Zhao, Y.; Dong, H.; Hou, S. Fabrication and application of a 3D-rGO electrochemical sensor for SO2 detection in ionic liquids. *Analytical Methods* **2023**, *15*, 3522−31.

(121) Du, H.; Xie, Y.; Wang, J. Nanomaterial-sensors for herbicides detection using electrochemical techniques and prospect applications. *TrAC Trends in Analytical Chemistry.* **2021**, *135*, 116178.

(122) Ismail, K. S. I. K.; Tajudin, A. A.; Ikeno, S.; Amir Hamzah, A. S. Heteroligand nanoarchitectonics of functionalized gold nanoparticle for Hg2+ detection. *J. Nanopart. Res.* **2022**, *24*, 253.

(123) Spagnolo, S.; De La Franier, B.; Davoudian, K.; Hianik, T.; Thompson, M. Detection of E. coli Bacteria in Milk by an Acoustic Wave Aptasensor with an Anti-Fouling Coating. *Sensors (Basel)* **2022**, *22*, 1853.

(124) Tessaro, L.; Aquino, A.; de Almeida Rodrigues, P.; Joshi, N.; Ferrari, R. G.; Conte-Junior, C. A. Nucleic Acid-Based Nanobiosensor (NAB) Used for Salmonella Detection in Foods: A Systematic Review. *Nanomaterials (Basel)* **2022**, *12*, 821.

(125) Behoftadeh, F.; Faezi Ghasemi, M.; Mojtahedi, A.; Issazadeh, K.; Golshekan, M.; Alaei, S. Development of a newly designed biosensor using multi-walled carbon nanotubes (MWCNTs) with gold nanoparticles (AuNPs) in the presence of acetaminophen for detection of Escherichia coli. *Arch. Microbiol.* **2023**, *205*, 70.

(126) Kaur, P.; Samir, R.; Sachan, K.; Karnwal, A.; Devgon, I. A Review on Clinical Manifestation and Treatment Regimens of UTI in Diabetic Patients. *Iranian Journal of Medical Microbiology* **2022**, *16*, 98−115.

(127) Sachan, R. S. K.; Mistry, V.; Dholaria, M.; Rana, A.; Devgon, I.; Ali, I.; et al. Overcoming Mycobacterium tuberculosis Drug Resistance: Novel Medications and Repositioning Strategies. *ACS Omega* **2023**, *8*, 32244−57.

(128) Harzand, F. V.; Anzani, S.; Soltani, A.; Zare, M.; Bakhshayesh, S.; Babapoor, A. Synthesis of advanced gold nanoparticles for biomedical applications. *Advances in Applied NanoBio-Technologies* **2022**, *3*, 13−9.

(129) Farzin, L.; Shamsipur, M.; Samandari, L.; Sheibani, S. HIV biosensors for early diagnosis of infection: The intertwine of nanotechnology with sensing strategies. *Talanta* **2020**, *206*, 120201.

(130) Shayesteh, O. H.; Ghavami, R. A novel label-free colorimetric aptasensor for sensitive determination of PSA biomarker using gold nanoparticles and a cationic polymer in human serum. *Spectrochim Acta A Mol. Biomol Spectrosc* **2020**, *226*, 117644.

(131) Shah, N. S.; Thotathil, V.; Zaidi, S. A.; Sheikh, H.; Mohamed, M.; Qureshi, A.; et al. Picomolar or beyond Limit of Detection Using Molecularly Imprinted Polymer-Based Electrochemical Sensors: A Review. *Biosensors 2022, Vol 12, Page 1107* **2022**, *12*, 1107.

(132) Gao, R.; Mao, Y.; Ma, C.; Wang, Y.; Jia, H.; Chen, X.; et al. SERS-Based Immunoassay of Myocardial Infarction Biomarkers on a Microfluidic Chip with Plasmonic Nanostripe Microcones. *ACS Appl. Mater. Interfaces* **2022**, *14*, 55414−22.

(133) Baryeh, K. Development of Quantitative Lateral Flow Strip Biosensors for the Detection of Cancer Biomarkers, 2019.

(134) Komal; Sachan, R. S. K.; Kashodhan, R. K.; Devgon, I.; Nisha; Khushboo; Mohammad Said Al-Tawaha, A. R.; Karnwal, A.; et al. Algal Protein: Future of Sustainable Food. *Food Microbial Sustainability* **2023**, 109−27.

(135) Sachan, R. S. K.; Karnwal, A. Advancement in cheese production technology. *Advances in Dairy Microbial Products* **2022**, 191−208.

(136) Gupta, R.; Kumar, A.; Kumar, S.; Pinnaka, A. K.; Singhal, N. K. Naked eye colorimetric detection of Escherichia coli using aptamer conjugated graphene oxide enclosed Gold nanoparticles. *Sens Actuators B Chem.* **2021**, *329*, 129100.

(137) Lee, J. W.; Choi, S. R.; Heo, J. H. Simultaneous Stabilization and Functionalization of Gold Nanoparticles via Biomolecule Conjugation: Progress and Perspectives. *ACS Appl. Mater. Interfaces* **2021**, *13*, 42311−28.

(138) Zhang, Y.; Juhas, M.; Kwok, C. K. Aptamers targeting SARS-COV-2: a promising tool to fight against COVID-19. *Trends Biotechnol* **2023**, *41*, 528.

(139) Ahmed, S.; Annu; Ikram, S.; Yudha, S. Biosynthesis of gold nanoparticles: A green approach. *J. Photochem. Photobiol. B* **2016**, *161*, 141−53.

(140) Caires, A. J.; Mansur, H. S.; Mansur, A. A. P.; Carvalho, S. M.; Lobato, Z. I. P.; dos Reis, J. K. P. Gold nanoparticle-carboxymethyl cellulose nanocolloids for detection of human immunodeficiency virus type-1 (HIV-1) using laser light scattering immunoassay. *Colloids Surf. B Biointerfaces* **2019**, *177*, 377−88.

(141) Huang, C.; Chen, Y.; Zhang, S.; Wu, J. Detecting, Extracting, and Monitoring Surface Water From Space Using Optical Sensors: A Review. *Reviews of Geophysics* **2018**, *56*, 333−60.

(142) Xu, J.; Li, Y.; Wang, L.; Huang, Y.; Liu, D.; Sun, R.; et al. A facile aptamer-based sensing strategy for dopamine through the fluorescence resonance energy transfer between rhodamine B and gold nanoparticles. *Dyes Pigm.* **2015**, *123*, 55−63.

(143) Mobed, A.; Hasanzadeh, M. Biosensing: The best alternative for conventional methods in detection of Alzheimer's disease biomarkers. *Int. J. Biol. Macromol.* **2020**, *161*, 59−71.

https://doi.org/10.1021/acsomega.3c10352
ACS Omega 2024, 9, 29966−29982