Green Synthesized Gold Nanoparticles From Biogenic Sources and Their Catalytic Applications

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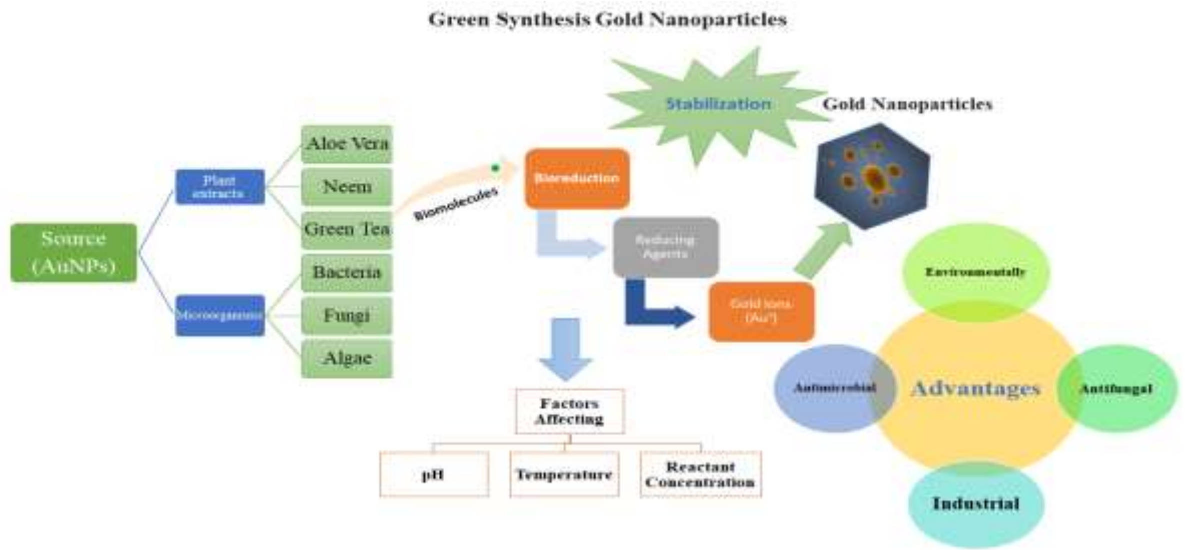
Abstract
The medicinal, environmental, and industrial uses of the green production of gold nanoparticles (AuNPs) have attracted much interest in recent years. This review aims to examine the significance of the green synthesis of AuNPs. Plant extracts, fungi, bacteria, and algae are all natural resources that may be used in the green synthesis of AuNPs. The synthesis of very stable and homogenous nanoparticles is achieved using these biogenic sources, reducing the environmental impact. Biogenic AuNPs are a promising alternative to chemically manufactured nanoparticles due to their claimed antimicrobial, antifungal, antioxidant, and anticancer effects. The green synthesis of AuNPs has used various biogenic sources, and this review study covers such sources and their features. The calming and stabilizing effects of plant extracts like *aloe vera*, *green tea*, and *neem* have been the subject of substantial research. The possibility of obtaining AuNPs from microorganisms, including bacteria, fungi, and algae, has also been investigated. We also discuss how pH, temperature, and reactant concentration all play a part in synthesizing AuNPs. This review study compares the catalytic activity of traditionally synthesized AuNPs with green-synthesized AuNPs based on significant research on the latter. It has been shown that green-synthesized AuNPs are more effective and efficient catalysts than their conventionally synthesized counterparts. Using biogenic sources also leads to the creation of more uniformly sized and stable nanoparticles. To sum up, the green synthesis of AuNPs is an exciting new direction in the environmentally responsible and long-term manufacture of nanoparticles with broad potential. Synthesizing extraordinarily stable and efficient nanoparticles from biogenic sources has several benefits, including a lower environmental impact. This reviews the present state of green synthesis of AuNPs and its significance for environmental awareness and concern.

Keywords: *Green synthesis, gold nanoparticles, eco-friendly, sustainable, renewable resources, cost-effective, biocompatible, non-toxic, biomedical applications, drug delivery, imaging, stability, therapeutic properties, reduced toxicity, and implications.*



1. Introduction

Nanotechnology has revolutionized several sectors, including biology, electronics, and catalysis, by providing novel answers to scientific inquiry and technical breakthroughs [1]. Due to their exceptional physicochemical characteristics, such as large surface area and superior optical, electrical, and catalytic capabilities, gold nanoparticles (AuNPs), among other nanoparticles, have drawn much interest [2]. However, the traditional chemical processes used to create AuNPs generate hazardous waste and require toxic chemicals, making them unsustainable and bad for the environment [3]. Using plant extracts, microbes, or other naturally occurring chemicals as reducing and stabilizing agents during the green synthesis of AuNPs produces AuNPs with distinctive physicochemical features [4]. Due to the number of plant extracts, their simplicity of extraction, and their capacity to create AuNPs of varied sizes and shapes, the use of plants as reducing agents for synthesizing AuNPs has attracted considerable interest [5]. The green synthesis of AuNPs provides several benefits over traditional approaches, including cheaper cost, decreased toxicity, excellent stability, and the possibility for large-scale manufacturing [6]. In light of this, green synthesis of AuNPs has become a potential alternative, giving ways for producing AuNPs that are environmentally benign and sustainable [7].

Much research has been done on the green synthesis of AuNPs utilizing plant extracts in recent years. Numerous studies have examined the impact of various plant extracts, including *Neem*, *Aloe Vera*, and *Turmeric*, on producing AuNPs [8]. Flavonoids, phenols, and terpenoids are a few phytochemicals present in these plant extracts that cause the reduction of Au ions to AuNPs [9]. Using plant extracts to make AuNPs green means that the phytochemicals in the extracts reduce the amount of Au ions, and then the biomolecules in the extracts stabilize the AuNPs that are left over [9].

Despite the potential benefits of producing AuNPs via plant extracts, several information gaps must be filled [10]. First, it's essential to comprehend the processes involved in the synthesis process and the characteristics of the produced AuNPs [11]. Second, it's crucial to thoroughly investigate how several variables, including temperature, pH, and concentration, affect the synthesis of AuNPs [12]. Thirdly, further research has to be done on the possible uses of green-synthesized AuNPs in numerous industries, including biomedicine and catalysis [13].

The use of plant extracts in the green synthesis of AuNPs and possible applications have been the subject of several investigations [14]. For instance, [15] In literature green synthesis of AuNPs utilizing the plant's aqueous extract, *Aristolochia indica*. Within 10 minutes of incubation, the plant extract successfully converted Au ions to AuNPs, according to the research. The artificial AuNPs had a typical size of 25 nm and were spherical [16]. Analysis using XRD, FTIR, and UV-Vis spectroscopy supported the stability and generation of the synthesized AuNPs [17]. The research also assessed using green-synthesized AuNPs as a catalyst for *p*-nitrophenol to *p*-aminophenol reduction [18]. The green-synthesized AuNPs outperformed commercial AuNPs regarding catalytic efficiency and stability, displaying a high catalytic activity and stability level [19].

Our research demonstrates the possibility of green synthesis of AuNPs as an option that is better for the environment and more sustainable than traditional approaches [20]. Furthermore, our findings indicate that green-synthesized AuNPs have outstanding catalytic characteristics, making them appropriate for application as catalysts in various industrial processes [21]. This was shown to be the case when we compared the catalytic activity of the two types of AuNPs [22]. In general, this work's findings contribute to the expanding body of research on the possible uses of green-synthesized AuNPs and underline the significance of their role in creating innovative and environmentally friendly solutions to problems in the fields of science and technology [23].

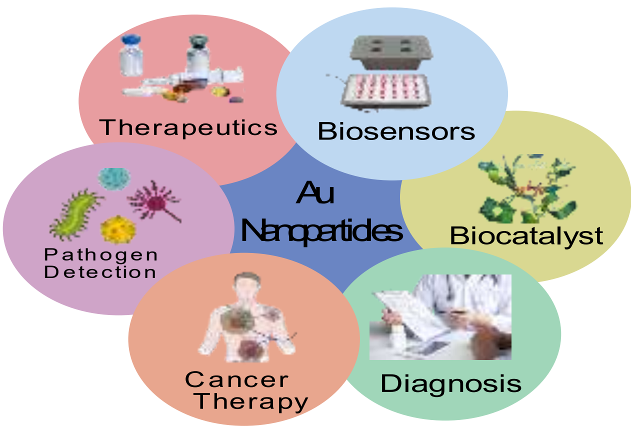


Figure 1 *Multifunctional applications of Au-nanoparticles*

1. Background Overview

Gold nanoparticles have been created for millennia; however, knowledge of their characteristics and uses has changed with time. The creation of the famed Lycurgus Cup using gold nanoparticles is one of the first examples of gold nanoparticle synthesis that has been documented. This cup glows red when illuminated from the inside but appears green when light passes through it. The gold nanoparticles in the glass absorb and scatter light in a distinctive manner, causing the appearance [24].

Early in the 20th century, Michael Faraday experimented with gold colloids and found that the color of the particles changed with particle size. He noticed that the bigger gold particles seemed blue, and the smaller gold particles appeared red. The interaction of light with the surface electrons of the gold nanoparticles causes this phenomenon, known as Plasmon resonance [25].

New techniques for creating gold nanoparticles with precise sizes and shapes were developed in the 1980s due to advances in nanotechnology and materials science. Initially, gold nanoparticles were created by chemical reduction processes, in which reducing agents reduced gold ions into gold nanoparticles. However, these techniques often used dangerous and poisonous substances that were bad for the environment and human health [26].

Growing interest has been shown in using environmentally friendly synthesis techniques to create gold nanoparticles in the twenty-first century. These techniques decrease and stabilize gold ions without using hazardous chemicals from natural sources, including plants, microbes, and other biogenic sources. Numerous benefits, such as improved biocompatibility, less environmental impact, and economic efficiency, come from using green synthesis techniques [27].

Present-day uses for gold nanoparticles include biomedical imaging, medication administration, catalysis, and electronics. Current research is focused on enhancing the effectiveness and scalability of gold nanoparticle synthesis. The capacity to manipulate the size and form of gold nanoparticles has opened up new potential for their usage in various industries [26]. Due to their distinctive optical, electrical, and catalytic capabilities, gold nanoparticles (AuNPs) have become increasingly common in various applications, including catalysis, biomedical imaging, drug administration, and electronics. Using hazardous and poisonous chemicals in the traditional procedures for making AuNPs puts the environment and human health at risk [28].

Due to its eco-friendliness and sustainability, green synthesis of AuNPs, a relatively novel technique, has attracted interest lately. To create AuNPs, natural resources, including plants, microbes, and other living entities, are used as reducing and stabilizing agents. Green synthesis techniques can displace conventional techniques because of their affordability, scalability, low toxicity, biocompatibility, and distinctive surface characteristics [29].

The scientific community has taken a keen interest in the green synthesis of AuNPs because of its potential to solve the rising environmental pollution issues and the need for environmentally friendly and sustainable methods. In addition to lessening the environmental effect, using natural resources as reducing and stabilizing agents generate a foundation for the creation of novel, environmentally friendly methods for the synthesis of diverse nanomaterials [30].

The potential uses of green synthesis of AuNPs in various industries, including medicine, agriculture, energy, and environmental remediation, further emphasize the significance of the process. Due to their unique qualities, AuNPs created using environmentally friendly processes are appealing for use in environmental remediation (such as removing heavy metals from water) and biological applications (such as medication delivery and cancer treatment) [30]. Green synthesis of AuNPs is a promising strategy with several benefits over traditional approaches, making it a required field of study in nanoscience and nanotechnology. It can fundamentally alter how we create nanomaterials, offering creative and long-lasting answers to major global problems, including pollution, energy, and healthcare [31].

2. Biogenic Sources for Green Gold Nanoparticle Synthesis

Plants, microbes, and other living things like fungi and algae are examples of biogenic sources for the green synthesis of gold nanoparticles. To create AuNPs from these sources without using hazardous chemicals, natural reducing and stabilizing substances such as enzymes, amino acids, and polysaccharides may be employed [32]. Scalability, low toxicity, and environmental friendliness are the only benefits of biogenic synthesis techniques over traditional ones. Additionally, the characteristics of biogenic sources may impact the surface characteristics, size, and shape of the synthesized AuNPs, making them desirable for various uses, including catalysis, medicine, and environmental remediation [6].

2.1 Plant extracts

Plant extract is one of the most popular biogenic sources for the green production of gold nanoparticles (AuNPs). Compared to traditional chemical procedures, using plant extracts as reducing and stabilizing agents for producing AuNPs has many benefits. Plant extracts may provide a sustainable method for synthesizing AuNPs since they are easily accessible, affordable, and environmentally favorable which is shown in figure 2 [26].

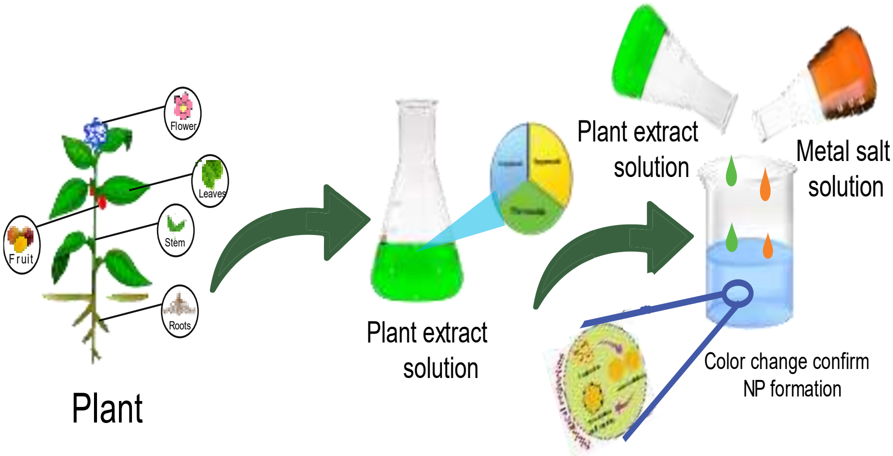


Figure 2 *Illustrated Plant-Facilitated Synthesis of Nanoparticles*

To create AuNPs, a plant extract containing natural reducing and stabilizing substances such as polyphenols, flavonoids, and terpenoids is combined with a gold salt solution. Through a redox process, these agents may decrease gold ions to produce AuNPs. The features of the plant extract, such as its pH, concentration, and phytochemical makeup, may affect the produced AuNPs' size, shape, and surface characteristics [33]. For the synthesis of AuNPs, plant extracts from a range of plant sources, including leaves, stems, roots, and fruits, have been employed. Solvent extraction, microwave-assisted extraction, and ultrasonic-assisted extraction are just a few of the techniques documented for extracting plant extracts. The gold salt solution combines the extracted plant extract to synthesize AuNPs [34].

AuNPs mediated by plant extracts have shown promise for various uses, including catalysis, biological imaging, drug administration, and sensing. For instance, it has been shown that AuNPs made from Aloe vera, garlic, ginger, and turmeric plant extracts have potent antibacterial and antifungal properties. Green tea, grapefruit, and pomegranate extracts were used to create AuNPs, which have shown anticancer potential. Moreover, compared to traditionally manufactured AuNPs, which often call for harsh chemicals and high temperatures, plant extract-mediated AuNPs may provide a biocompatible and non-toxic alternative [35].

Despite the benefits, there are several difficulties with producing AuNPs using plant extracts. The repeatability and scalability of the synthesis process may be impacted by the characteristics of the plant extract, which may reduce the likelihood of commercialization. Additionally, contaminants in the plant extract may impact the stability and shelf life of the produced AuNPs. To assure repeatability and scalability, more research is required to improve and standardize the synthesis methodology employing plant extracts [36].

2.2 Microorganisms

To produce green gold nanoparticles, microorganisms, including bacteria, fungi, and algae, have been employed as biogenic sources. The microbial-mediated production of gold nanoparticles is an approach to nanotechnology that has promise since it is environmentally benign and sustainable. The mechanism of the intracellular-cell-bound synthesis of gold nanoparticles is shown in Figure 3 [31].

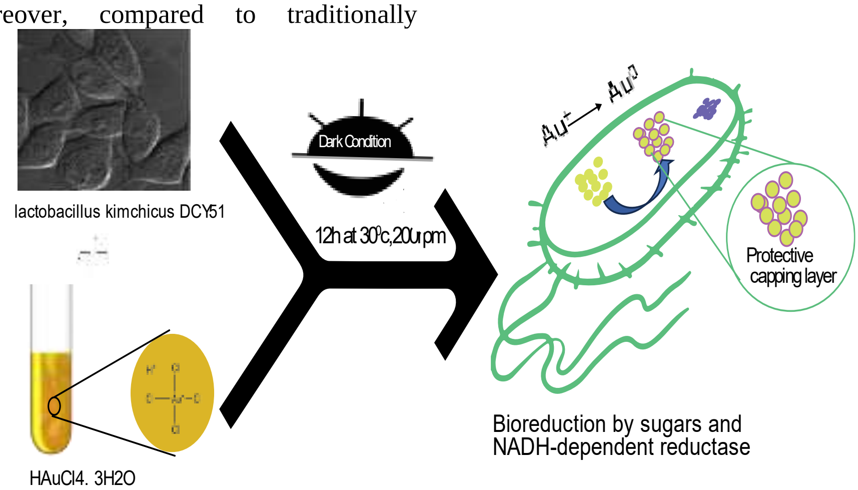


Figure 3 *Mechanism of the intracellular-cell bound synthesis of gold nanoparticles (AuNPs) using L. kimchicus DCY51T (Mughal et al., 2021)*

It has been shown that bacteria, including *Escherichia coli*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*, can create gold nanoparticles by reducing gold ions. It has also been done using fungi like *Aspergillus niger*, *Penicillium brevicompactum*, and *Fusarium oxysporum* to create gold nanoparticles. It has also been noted that some algae, including *Dunaliella salina*, *Spirogyra sp*., and *Chlorella vulgaris*, may create gold nanoparticles [37].

Enzymes like reductases, which reduce gold ions to gold nanoparticles, are secreted during the microbial-mediated creation of gold nanoparticles. Changing the parameters of the reaction and the kind of microorganisms utilized may alter the size, shape, and stability of the nanoparticles. One benefit of employing microbes for the environmentally friendly production of gold nanoparticles is their capacity to create vast numbers of nanoparticles. The synthesis procedure is relatively quick and may be done in a small reaction space. Microorganisms can also create nanoparticles with unique qualities, including antibacterial and anticancer capabilities, making them desirable for a range of biomedical applications [38].

However, the ecological manufacture of gold nanoparticles utilizing microbes is not without difficulties. Variations in the microorganisms' development environments may impact the synthesis process, which can change the size and form of the nanoparticles. Extracellular chemicals that certain microbes may create can also impact the stability of the nanoparticles or interfere with the production process. Overall, producing gold nanoparticles by microbes has enormous potential for advancing environmentally friendly and sustainable nanotechnology [30].

2.3 Other biogenic sources

Several more biogenic sources have been investigated for the green production of gold nanoparticles, plant extracts, and microbes. Fungi, algae, and even animal sources like eggshells are a few of these sources. Due to their capacity to create enzymes that can decrease gold ions, fungi have been demonstrated to be helpful in manufacturing gold nanoparticles. For instance, gold nanoparticles with 5-100 nm diameters have been produced using the fungus Aspergillus niger [39].

On the other hand, algae have proven successful in producing gold nanoparticles because of their high photosynthetic activity and capacity to collect gold ions. For instance, a green alga called *Chlorella vulgaris* has been utilized to create gold nanoparticles with diameters ranging from 30 to 100 nm. Another biogenic material that has been used for the environmentally friendly creation of gold nanoparticles is eggshells. Calcium carbonate, which may be utilized as a reducing agent to create gold nanoparticles, is present in eggshells [40].

The eggshell membrane can stabilize the nanoparticles. Additionally, nanocomposites containing gold nanoparticles may be created using eggshell membranes. Green synthesis of gold nanoparticles using various biogenic sources presents a viable alternative to traditional techniques. These biogenic sources provide an economical and environmentally beneficial method with exceptional benefits, including the ability to produce on a large scale and customizable size and shape control [41].

2.4 Properties of biogenic sources

Plant extracts and microorganisms are examples of biogenic sources with unique qualities that make them perfect for the environmentally friendly production of gold nanoparticles. These qualities consist of:

Bioavailability: Getting significant amounts of biological sources is simple and quick. They are a quick-to-grow or quick-to-harvest source of sustainable and affordable raw materials for nanoparticle production [42]. Bioreduction capacity: Biological sources can reduce metal ions to nanoparticles through several metabolic processes. For instance, many phytochemicals found in plant extracts, such as flavonoids and terpenoids, may function as reducing agents to transform metal ions into nanoparticles [33].

Stability: Biogenic sources may serve as stabilizing agents to stop the nanoparticles from clumping or oxidizing. This is because biomolecules including proteins, polysaccharides, and polyphenols exist and may bind to the surface of nanoparticles to create a protective coating [43]. Functionalization: The nanoparticles may be functionalized by adding certain functional groups to their surface using biogenic sources. This is possible by including specific biomolecules in the reaction mixture during nanoparticle manufacturing.

Biocompatibility: Biological sources are non-toxic and biocompatible, so they are excellent for biomedical applications. When biogenic sources are used to manufacture nanoparticles, biocompatible nanoparticles that do not trigger an immune response may be produced [44].

Diversity: A wide range of biogenic sources are accessible, each with a different chemical makeup and set of characteristics. As a result, nanoparticles with various dimensions, forms, and surface properties may be created. The unique qualities of biogenic sources make them a desirable substitute for traditional chemical processes for producing gold nanoparticles. They are a sustainable and flexible solution for nanoparticle production since they are biocompatible, cost-efficient, and environmentally friendly [45].

3. Green synthesis of gold nanoparticles

The reduction of gold ions using natural substances like plant extracts, microorganisms, or other environmentally benign sources is known as the "green synthesis" of gold nanoparticles. Depending on the source, green synthesis' precise method may change. Here are a few examples of environmentally friendly synthetic chemical processes for gold nanoparticles [5].

3.1 Synthesis mediated by plant extracts

The plant extract promotes the creation of gold nanoparticles by acting as reducing and stabilizing agents. For instance, phytochemicals found in plant extracts, including flavonoids, phenols, and terpenoids, may lower the gold ions and stop the formation of nanoparticles from aggregating [46].

$AuCl_4^-$ + plant extract → Au nanoparticles + Cl^- + other by-products

3.2 Microbial-mediated Synthesis

Microbes, including bacteria, fungi, and yeast, may also reduce gold ions to form gold nanoparticles. In this instance, reducing agents are the microbial cell extract or the released enzymes. For instance, bacteria may create the enzyme nitrate reductase, reducing gold ions and making gold nanoparticles [47].

$AuCl_4^-$ + microbe extract → Au nanoparticles + Cl^- + other by-products

3.3 Green reducing agents

The environmentally friendly synthesis of gold nanoparticles may also be accomplished using green reducing agents, including vitamin C, glucose, and citric acid. Without the need for hazardous chemicals or high-energy inputs, these reducing agents can efficiently reduce the gold ions to produce stable nanoparticles. For instance, vitamin C's hydroxyl and carbonyl groups may decrease and stabilize the produced gold nanoparticles [48].

$AuCl_4^-$ + green reducing agent → Au nanoparticles + Cl^- + other by-products

3.4 Factors affecting the synthesis of gold nanoparticles

Several variables are involved in the synthesis of gold nanoparticles, which may have an impact on their creation and characteristics. Some important elements influencing the creation of gold nanoparticles are as follows:

***Table 1** Factors affecting the synthesis of gold nanoparticles*

Factor	Effect	Reference
pH	Affects the size, shape, and stability of nanoparticles	[49]
Time	Influences the size and morphology of the nanoparticles	[50]
Temperature	Affects the rate of reaction and the size of nanoparticles	[51]
Concentration	Affects the size and morphology of nanoparticles	[52]
Reducing agent	Affects the size and shape of nanoparticles	[53]
Stabilizing agent	Determines the stability of nanoparticles and their toxicity	[54]

4. Mechanism of Green Synthesis of Gold Nanoparticles

The reduction of gold ions and stabilization of the nanoparticles are the two primary processes in the green synthesis of gold nanoparticles.

4.1 Reduction of gold ions

During the green synthesis of gold nanoparticles, biogenic reducing agents convert gold ions (Au^{3+}) to gold nanoparticles (Au0). Microorganisms or plant extracts may function as reducing agents and their mechanism is shown in Figure 4. Typically, the biogenic reducing agent and gold ions are present in an aqueous solution during the reduction process. Numerous biomolecules, including flavonoids, terpenoids, alkaloids, and polyphenols, are included in the reducing agents. These biomolecules may operate as reducing agents because they contain functional groups like hydroxyl and carbonyl groups [55].

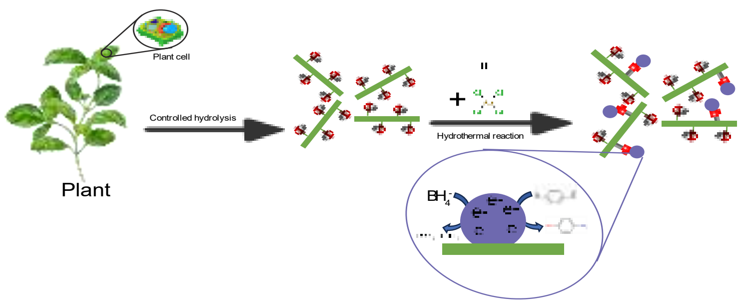


***Figure 4** Visual Depiction of the Mechanism for Catalytic Reduction of 4-NP using Au NPs@CNs (Wu et al., 2014)*

The reduction process begins with the transfer of electrons from the gold ions to the reducing agents, which results in the production of gold atoms. The result is the formation of gold nanoparticles from these gold atoms. By altering the reaction mixture's temperature, pH, and reducing agent concentrations, it is possible to regulate the nanoparticles' size, shape, and morphology [56].

4.2 Nanoparticle stabilization:

Gold nanoparticles must be stabilized to stop them from aggregating and to keep them stable. Proteins, amino acids, and polysaccharides are examples of biogenic capping agents that may attach to the surface of the nanoparticles and stop them from aggregating, which is how the stabilization is accomplished. The capping agents also make the nanoparticles more stable and biocompatible, making them appropriate for various uses. Electrostatic or steric stabilization methods may also be used to stabilize the nanoparticles [57].

4.3 Techniques for characterizing gold nanoparticles:

Gold nanoparticles are crucial for determining their size, shape, surface area, and other physicochemical characteristics. Using UV-Vis spectroscopy, transmission electron microscopy (TEM), dynamic light scattering (DLS), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR), scientists can look at gold nanoparticles made in ways that are good for the environment [58].

These methods make it possible to identify the capping agents present on the surface of the nanoparticles and their size and shape. Generally, biogenic reducing agents are used to turn gold ions into stable nanoparticles with well-defined sizes and shapes, and then capping agents stabilize the nanoparticles and stop them from aggregating. The physicochemical characteristics of the nanoparticles are then determined using characterization procedures [59].

5. Advantages of Green Synthesis of Gold Nanoparticles

The term "green synthesis" of gold nanoparticles describes the creation of nanoparticles by eco-friendly techniques without potentially harmful substances or procedures. The following are some benefits of producing gold nanoparticles in a green manner [60].

5.1 Eco-friendliness

One of the main benefits of making gold nanoparticles via green synthesis is their eco-friendliness. This process is regarded as eco-friendly since it creates little to no hazardous waste and employs natural and renewable resources as its initial starting components. Contrarily, traditional techniques for making gold nanoparticles sometimes depend on poisonous substances that might produce dangerous byproducts, including sodium borohydride [61].

Because they depend on freely accessible and renewable natural resources, green synthesis techniques that employ plant extracts or microorganisms as reducing and stabilizing agents are incredibly environmentally benign. For instance, common plant species that are prevalent around the globe may be used to make plant extracts. Microorganisms may also be readily cultivated in the lab, making them a reliable supply of reducing and stabilizing agents. Examples of these organisms include bacteria and fungi [62].

The green synthesis of gold nanoparticles is not only environmentally benign but can also lower the carbon footprint of nanoparticle manufacturing. This is due to the method's ability to be adjusted to decrease energy usage, which may help lessen greenhouse gas emissions and other adverse environmental effects. The green synthesis of gold nanoparticles is an intriguing alternative to traditional techniques due to its eco-friendliness, especially in applications where sustainability and environmental impact are key factors [63].

5.2 Biocompatibility

One of the key benefits of the environmentally friendly production of gold nanoparticles is that they are biocompatible, an essential component of any biomedical application. "Biocompatibility" describes a material's capacity to coexist peacefully with biological tissues. Because gold nanoparticles are increasingly employed in biological applications such as medication administration, diagnostic imaging, and cancer treatment, biocompatibility is crucial [64].

Compared to traditional synthesis techniques, the green production of gold nanoparticles has many benefits in terms of biocompatibility:

1. The danger of toxicity and negative impacts on living creatures is decreased when natural materials are used for synthesis.
2. Meticulous control over the size and form of the nanoparticles throughout the production process improves their biocompatibility and lowers the likelihood of inflammation and an immunological reaction [34].
3. To increase the biocompatibility of the nanoparticles and lessen immune system clearance, the surface of the particles may be altered with biocompatible coatings, such as polyethylene glycol. (PEG) [65].

5.3 Cost-effectiveness

Another benefit of environmentally friendly gold nanoparticle production is its affordability. Traditional techniques for producing gold nanoparticles often require expensive ingredients and equipment, such as specialized reactors and hazardous reducing agents. In contrast, green synthesis techniques often employ less complicated, less costly, and easily accessible starting ingredients [66].

For instance, various plant species with low cultivation costs may be employed to produce plant extracts for green synthesis. Similarly, microorganisms employed in green synthesis may be readily cultivated in a lab environment and derived from natural sources, giving them an affordable alternative to traditional techniques [20]. Additionally, since poisonous byproducts and hazardous materials are not produced, green synthesis may lower the expenses related to waste management. As a result, green synthesis is both economical and ecologically responsible. Overall, green synthesis is a desirable choice for the mass manufacturing of gold nanoparticles due to its affordability [67].

5.4 Antimicrobial properties

The benefits of environmentally friendly gold nanoparticle synthesis (AuNPs) include their antibacterial characteristics, which have recently received much attention. It has been shown that AuNPs exhibit antibacterial action against various pathogens, including viruses, fungi, and bacteria [68]. Physical and chemical mechanisms are believed to be involved in the antibacterial effect of AuNPs. Due to their tiny size, nanoparticles may enter the cell walls of microorganisms and interfere with their regular cellular functions. Additionally, the AuNPs' surface may interact with cellular membranes, damaging them and increasing their permeability [69].

AuNPs may be employed as transporters for antimicrobial substances such as antibiotics, antifungal medications, and their direct antimicrobial properties. Nanoparticles may boost their effectiveness by improving these drugs' stability and allowing for more precise distribution to the infection site [70]. Potential uses for AuNPs' antibacterial abilities include treating water, food, and disease, among other industries. For instance, in food packaging, AuNPs may be used to prolong the shelf life of perishable goods and in wound dressings and coatings to avoid infections. They may also be used in water treatment to rid drinking water of dangerous microbes. AuNPs' antibacterial abilities are a promising study area with various possible uses. Additional study is necessary to completely comprehend the processes of action and maximize their usage in diverse applications [71].

Table 2 *Antibacterial activity by organisms tested*

Organisms tested	**Green synthesis method**	**Antibacterial activity**	**Study**
Escherichia coli, Staphylococcus aureus	Plant extract	Inhibited growth	[72]
Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus	Leaf extract	Inhibited growth	[73]
Escherichia coli, Pseudomonas aeru ginosa, Staphylococcus aureus	Plant extract	Inhibited growth	[74]
Escherichia coli, Pseudomonas aeruginosa, Salmonella typhi, Staphylococcus aureus	Fruit extract	Inhibited growth	[75]
Bacillus subtilis, Staphylococcus aureus	Seed extract	Inhibited growth	[76]
Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus	Fungal extract	Inhibited growth	[77]

Table 3 *Green-synthesized AuNPs exhibit strong antibacterial activity against both Gram-negative and Gram-positive bacteria*

Bacteria	**Gram Stain**	**Antibacterial Activity**	**Study**
Escherichia coli	Negative	Strong	[78]
Staphylococcus aureus	Positive	Strong	[79]
Pseudomonas aeruginosa	Negative	Strong	[80]
Salmonella typhi	Negative	Strong	[81]
Bacillus subtilis	Positive	Strong	[76]

5.5 Catalytic activity

The catalytic activity of gold nanoparticles (AuNPs), studied in various domains, including environmental remediation, energy, and chemical processes, is one of the main benefits of green gold nanoparticle manufacturing. Due to their tiny size, large surface area, and electrical structure, AuNPs produced using environmentally friendly processes have distinctive catalytic capabilities [5].

The surface Plasmon resonance (SPR) effect, the collective oscillation of electrons on the nanoparticle surface upon stimulation with light, allows AuNPs to interact with other molecules and produce catalysis. This characteristic may be tailored by adjusting the nanoparticles' size and form. It has been discovered that AuNPs show catalytic activity in several processes, including hydrogenation, oxidation, and reduction [21]. For instance, they may be employed as catalysts that convert nitroaromatic chemicals into amino-aromatic compounds, which has significant uses in the pharmaceutical sector. Similar to this, AuNPs have been used as catalysts for converting alcohols into aldehydes or ketones, a process that is useful in synthesizing organic compounds [82].

AuNPs may also modify their surface with other functional groups, such as amino or carboxyl groups, to increase their catalytic activity. They have increased catalytic activity from this alteration, enabling selective adsorption of specific molecules onto the nanoparticle surface. In conclusion, due to their catalytic activity, green-produced AuNPs are potential candidates for various applications, including catalysis, chemical synthesis, and environmental remediation [83].

Table 4 *Compare the catalytic activity of gold nanoparticles*

Parameters	**Traditional Synthesis**	**Green Synthesis**
Size	Usually larger	Smaller and uniform
Shape	Random	Controlled
Stability	Often unstable	More stable
Efficiency	Lower	Higher
Reaction time	Longer	Shorter
Cost	Higher	Lower
Toxicity	More toxic chemicals used	Fewer toxic chemicals used
Environmental impact	Higher	Lower

6. Applications of Green Synthesis of Gold Nanoparticles

There are several potential uses for the green production of gold nanoparticles (AuNPs), including in biomedicine, environmental cleanup, energy, agriculture, and other fields. Due to their distinctive optical, electrical, and physical characteristics, gold nanoparticles (AuNPs) have drawn much interest in biological applications. The green synthesis of AuNPs provides a non-toxic and economical approach to creating nanoparticles for numerous biomedical applications. The following are some of the leading biomedical uses for greenly produced AuNPs [84].

Imaging and diagnosis: AuNPs are effective contrast agents that may be employed in imaging and diagnosis. AuNPs have significant absorption and scattering characteristics due to their large surface area-to-volume ratio, making them perfect for diagnostic imaging methods, including computed tomography (CT) and optical coherence tomography (OCT) [85]. Drug Delivery: In recent years, there has been a lot of interest in using AuNPs as drug delivery systems. Because of their tiny size and ability to quickly pass through cellular barriers, AuNPs can be functionalized with medicines, proteins, and other therapeutic agents. They may increase therapeutic effectiveness while lowering adverse effects since they are the perfect vehicle for focused medication delivery [86].

Cancer Treatment: AuNPs have a variety of applications in the treatment of cancer, including photothermal therapy (PTT) and photodynamic therapy (PDT). When exposed to near-infrared light, AuNPs functionalized with a cancer-targeting chemical transform the absorbed energy into heat, which causes localized tumor death. AuNPs may be employed in PDT as photosensitizers, which produce reactive oxygen species when exposed to light and cause the death of cancer cells [87].

Wound Healing: Due to their antibacterial and anti-inflammatory characteristics, AuNPs have been shown to enhance wound healing. Additionally, AuNPs may boost collagen synthesis and encourage angiogenesis, which can hasten the healing of wounds [88]. Biosensors: AuNPs may be employed as biosensors to identify a variety of biomolecules, including enzymes, proteins, and DNA. AuNPs are perfect for colorimetric detection due to their distinct optical characteristics, and their tiny size enables the fabrication of very sensitive biosensors. Overall, the green production of AuNPs makes it possible to produce biocompatible and affordable nanoparticles for numerous biomedical applications [89].

6.1 Environmental remediation

Gold nanoparticles (AuNPs) produced using environmentally friendly technologies have unique physical and chemical characteristics that make them useful in applications for environmental restoration. Heavy metals, organic contaminants, dyes, and other environmental pollutants may be removed using AuNPs [90].

AuNPs' use as catalysts to break down organic contaminants is one of their main uses in environmental restoration. It has been shown that AuNPs may efficiently break down contaminants such as phenolic chemicals, dyes, and polycyclic aromatic hydrocarbons (PAHs). Adsorption of the pollutant onto the surface of the AuNPs is the first step in the catalytic degradation process. The next step is the transfer of electrons from the AuNPs to the pollutant molecules, which creates reactive oxygen species that may break down the pollutant [91].

AuNPs have also been utilized to filter out heavy metals from polluted water sources. Lead, mercury, and cadmium may all be effectively adsorbed thanks to the large surface area of AuNPs. A magnetic field or filtration may quickly separate the AuNPs from the water in such cases. AuNPs have also been shown to be efficient in the adsorption and subsequent photocatalytic destruction of organic contaminants in water. Overall, the application of green-synthesized AuNPs in environmental remediation has shown considerable promise because of their high effectiveness, low toxicity, and biocompatibility [92].

6.2 Energy applications

Due to their distinctive optical and catalytic capabilities, gold nanoparticles (AuNPs) have a bright future in energy applications. AuNPs are used in solar energy conversion because of their effective light absorption and scattering properties [21].AuNPs may be used as plasmonic materials in solar cells to increase light absorption and boost the conversion efficiency of the cells in solar energy harvesting. To produce hydrogen by water splitting, a potential renewable energy source, AuNPs have also been employed as catalysts. AuNPs' catalytic solid activity is due to their vast surface area and distinctive electrical characteristics, which make it easier to cleave water molecules apart [93].

AuNPs have been used in fuel cells as catalysts for the oxygen reduction process (ORR), a crucial stage in transforming chemical energy into electrical energy. It has been shown that using AuNPs as ORR catalysts increases the fuel cells' durability and efficiency. Due to their excellent thermal stability and conductivity, AuNPs have also been employed as lubricants and additives in energy storage systems like batteries and supercapacitors. It has been shown that adding AuNPs to these devices would improve their functionality and lengthen their useful lives [93].

6.3 Agricultural applications

Agricultural uses for gold nanoparticles (AuNPs) made by green synthesis are possible. It may promote plant growth, increase agricultural output, and provide pest and disease protection. It has been found that AuNPs made from plant extracts and microorganisms promote seed germination and plant development. The nanoparticles are thought to serve as carriers for nutrients and growth elements, enhancing plant development [34].

Additionally, since they have shown potential action against various pests and diseases, AuNPs may be used as Nano pesticides. According to studies, plant extracts are used to make AuNPs, which are used to combat fungal infections in crops, including wheat, rice, and tomatoes. Since the nanoparticles were found to stop the growth of fungus spores and mycelia, they could be an excellent alternative to chemical fungicides [30].

Additionally, AuNPs may be utilized to clean up polluted water and land. The nanoparticles may lessen their toxicity by removing heavy metals and organic contaminants from polluted water and soil. A new field of study is the use of AuNPs for water filtration. It has been noted that AuNPs created utilizing plant extracts may successfully remove contaminants from polluted water [94].

AuNPs may also be used as biosensors to identify environmental toxins, such as diseases, heavy metals, and pesticides. The nanoparticles are an excellent choice for environmental monitoring due to their great sensitivity and selectivity. Additional study is still required to fully comprehend the potential uses of AuNPs in agriculture and address concerns about their toxicity and environmental effects [30].

6.4 Other applications

Gold nanoparticles (AuNPs) produced by green synthesis have potential applications in several other sectors besides those described above. The following are some more uses for AuNPs:

Food business: To extend the shelf life of food goods, AuNPs may be employed as a food packaging material in the food industry. They may also be utilized as antioxidants, food additives, and preservatives [95]. Textile industry: AuNPs may be utilized to create textiles with distinctive qualities, including antibacterial, antifungal, and UV protection features in the textile business.

Cosmetics: Due to their anti-inflammatory and antioxidant qualities, AuNPs may be employed in cosmetics as a delivery system for active substances [96].

Water purification: AuNPs may purify water by removing hazardous elements such as heavy metals and organic pollutants. Sensing and detection: AuNPs can detect various analytes, including glucose, DNA, proteins, and heavy metals. Additionally, they may be utilized for environmental monitoring, food safety testing, and medical diagnostics [97].

Nanoelectronics: Due to their distinctive electrical and optical characteristics, AuNPs may be employed in Nanoelectronics as interconnects, switches, and memory devices. Art conservation: Because AuNPs may cover an object's surface with a protective layer, they can be utilized to conserve and restore works of art [98]. Before these applications can be completely realized, however, issues and restrictions must be resolved. These include the synthesis process's capacity to scale up, the nanoparticles' stability and repeatability, and the nanoparticles' potential toxicity and environmental effects. However, the many uses of green-synthesized AuNPs offer considerable potential for future industrial developments [20].

6.5 Challenges and limitation of applications

Due to its eco-friendliness, affordability, and potential biological and environmental uses, the green synthesis of gold nanoparticles (AuNPs) has become a viable alternative to traditional chemical procedures. However, using AuNPs produced by green synthesis has several difficulties and restrictions [99].

Reproducibility: The absence of reproducibility is one of the significant problems with green synthesis. Temperature, pH, and reagent concentration are just a few variables that affect the synthesis process and particle size, shape, and stability. Lack of consistency in the techniques used to create AuNPs from various biogenic sources might cause variances in the materials' characteristics and uses [100].

Toxicity: Although biocompatibility makes green-synthesized AuNPs typically harmless, there are still worries regarding their possible toxicity. Size, shape, surface charge, and coating material are only a few variables that affect how hazardous AuNPs are.

Stability: AuNPs made using environmentally friendly techniques tend to be less stable than those created using chemical techniques, which might restrict their shelf life and applicability [100].

Characterization: Because of their tiny size and intricate surface chemistry, AuNPs made using green techniques may be challenging to characterize. To guarantee the caliber and consistency of the produced nanoparticles, it is crucial to apply cutting-edge analytical methods, including X-ray diffraction (XRD), dynamic light scattering (DLS), and transmission electron microscopy (TEM) [101].

Application restrictions: Although green-synthesized AuNPs have potential uses, few fields currently use them. To fully explore their potential in numerous domains, further study is required. In conclusion, green chemical synthesis of AuNPs is a promising method with many benefits over the former. Several issues and restrictions related to their use still need to be resolved to guarantee their safe and efficient usage in diverse domains [102].

7. Toxicity of Green Synthesis of Gold Nanoparticles (AuNPs)

The use of green synthesis of gold nanoparticles (AuNPs) must take their toxicity into account. Although green synthesis is often seen as a secure and environmentally benign way to create AuNPs, carefully assessing their possible toxicity is still essential. According to specific research, AuNPs may be hazardous to the environment, animals, and human cells. However, the size, shape, surface charge, concentration, exposure route, and duration all significantly influence how poisonous AuNPs are. Further study is required to completely comprehend the toxicity of green-synthesized AuNPs and provide helpful safety criteria for using them in diverse applications [102].

7.1 In vitro and in vivo studies

Studies are being done in the lab and on animals to determine how harmful gold nanoparticles (AuNPs) produced by green synthesis are. In contrast to in vivo investigations, which deliver nanoparticles to living things, in vitro, research entails exposing cells or tissues to synthetic AuNPs [103].

The toxicity of AuNPs varies according to several variables, including particle size, concentration, surface charge, and coating, according to in vitro research. Because they have a higher surface area-to-volume ratio than bigger AuNPs, small AuNPs (10 nm) are more hazardous than larger ones. Additionally, it has been shown that positively charged AuNPs are more hazardous than negatively charged ones. Their coating may also impact the toxicity of AuNPs. It has been discovered that PEG-coated AuNPs are less hazardous than uncoated AuNPs [104].

According to in vivo research, the mode of administration, dose, and dispersion of AuNPs affect their toxicity. According to studies, inhaling excessive amounts of AuNPs may irritate the lungs, while intravenous injections of AuNPs can harm the liver and kidneys. However, research has also shown that tiny dosages of AuNPs may be given safely without having a negative impact [105].

Overall, in vitro and in vivo research has shed light on the toxicity of green-synthesized AuNPs and the variables that affect it. These investigations are crucial for creating secure and efficient AuNPs applications across various disciplines [47]. Here is an example of a table summarizing some of the results from tests on the toxicity of environmentally friendly gold nanoparticles (AuNPs) conducted in vitro and in vivo:

Table 5 *Gold nanoparticles (AuNPs) conducted in vitro and in vivo*

Cell or Animal Model	Exposure Conditions	Results	Study
Human lung cancer cells	24-hour exposure to varying concentrations of AuNPs	Decreased cell viability and increased oxidative stress at high concentrations	[106]
Zebrafish embryos	96-hour exposure to varying concentrations of AuNPs	Increased mortality, developmental abnormalities, and oxidative stress at high concentrations	[107]
Mice	Single intravenous injection of AuNPs	No adverse effects on liver or kidney function, but accumulation in spleen and lungs	[108]
Human liver cells	24-hour exposure to varying concentrations of AuNPs	Decreased cell viability and increased inflammation and oxidative stress at high concentrations	[109]
Human blood cells	24-hour exposure to varying concentrations of AuNPs	No significant effects on cell viability, but increased oxidative stress and DNA damage at high concentrations	[109]

7.2 Possible mechanism of toxicity

Some variables, including size, shape, surface charge, concentration, and surface coating, affect how poisonous AuNPs are. AuNPs' potential toxicological processes may be divided into two categories: Physical interactions: Due to their vast surface area to volume ratio, which may result in oxidative stress, DNA damage, and membrane rupture, AuNPs can physically harm cells and tissues at high concentrations. The physical contact of AuNPs with cell membranes can alter membrane permeability, leading to cellular malfunction and mortality [110].

Biochemical interactions: AuNPs interact with biomolecules such as proteins, lipids, and DNA in their biochemical interactions with biological systems. Their surface charge and functional groups may influence the interaction of AuNPs with biomolecules and their harmful consequences. Protein denaturation or aggregation caused by interactions between AuNPs and proteins may impair the proteins' functionality. The interactions of AuNPs with DNA may cause DNA damage that leads to cancerous mutations [111].

Studies conducted in vitro have shown that AuNPs may harm cells by causing oxidative stress, genotoxicity, and cytotoxicity. AuNPs have been linked to organ toxicity, inflammation, and immune toxicity in vivo. The particles' concentration, size, and surface coating all affect how hazardous AuNPs are. Numerous studies have shown that, compared to chemically produced AuNPs, biogenic sources such as plant extracts and microorganisms may produce AuNPs that are less hazardous. Creating AuNPs with desired features for particular applications while lowering the toxicity of the particles is another benefit of using green synthesis [112].

7.3 Migration of toxicity

The capacity of nanoparticles to move from the exposure site to other sections of the body, potentially causing systemic toxicity, is called "migration of toxicity." The migration and toxicity of green-produced gold nanoparticles (AuNPs) have been studied both in vitro and in vivo [113]. Studies conducted in vitro have shown that AuNPs may enter cells, interact with biological elements, and cause cytotoxicity and genotoxicity. However, altering the size, shape, surface charge, and surface chemistry of AuNPs may control how hazardous they are. For instance, owing to their greater surface area and higher capacity to produce reactive oxygen species (ROS), smaller AuNPs are more hazardous than bigger ones [114].

AuNPs may build up in different organs, such as the liver, spleen, and kidneys, which might result in organ damage, according to in vivo research. It has been shown that AuNP size and surface charge affect their biodistribution and accumulation in several organs. In the liver and spleen, for instance, positively charged AuNPs build up more, while negatively charged

AuNPs build up more in the kidneys [115]. Additionally, the migration and toxicity of AuNPs might be impacted by how they are administered. While oral administration of AuNPs may result in their absorption into the circulation and subsequent distribution to different organs, inhalation of AuNPs can cause their deposition in the respiratory tract [116]. Particle size, surface charge, surface chemistry, and administration method are only a few of the variables that might affect how poisonous green-generated AuNPs migrate. Further study is required to completely comprehend the processes driving the migration of AuNPs' toxicity and to create methods to reduce any possible negative consequences [117].

Conclusion

Gold nanoparticle (AuNPs) manufacturing that is gentle on the planet has a long way to go before it can be considered fully explored. Some areas that need further investigation are: Developing more efficient and reproducible procedures might enhance the quality, quantity, and stability of AuNPs generated from different biogenic sources. The understanding and characterization of AuNPs properties. These questions may be better understood and their applications better guided by more research into AuNPs' size, shape, surface charge, stability, and structure-function correlations. More study is needed to determine the potential toxicity and safety issues associated with using AuNPs in various applications and to develop methods for mitigating such risks. The green synthesis of AuNPs is a fascinating and rapidly growing field of research with substantial implications for numerous applications.

Possible reductions in environmental and human health concerns connected with existing procedures might result from using organic, sustainable, and environmentally friendly methods to synthesize AuNPs. Moreover, due to their unique properties, AuNPs are attractive candidates for several applications in biomedicine, environmental remediation, energy production, and agriculture. Green-synthesized AuNPs have several potential applications, including targeted drug administration, imaging, biosensors, catalysis, and water purification. These applications could create new employment in various industries because of their capacity to provide high-value products and services at a low cost and sustainably. Despite the benefits, there are drawbacks to employing AuNPs, such as toxicity concerns, regulations, and a need for standardized synthesis methods. Additional study is required to address these concerns and assure the safe and effective use of AuNPs in a wide range of applications. The ethical and social implications of the widespread use of nanotechnology will need to be carefully considered, as will the need to develop responsible and sustainable techniques that promote environmental and social justice.

CRediT authorship contribution statement

Ahsan: Conceptualization,Methodology, Investigation, Software, Writing - Original Draft, Writing - Review & Editing. **Samra Barkaat:** Data curation, Writing - Review & Editing, Supervision. **Muhammad Sajid Ali:** Visualization, Writing - Review & Editing. **Numra Shehzadi:** Writing - Original Draft, Writing - Review & Editing, Formal analysis. **Shazia Naheed:** Writing - Review & Editing, Software, Validation, Formal analysis, Supervision. **Zaheer Ahmad:** Writing - Review & Editing, Software, Validation, Formal analysis, Supervision. **Hefza Shamim:** Writing- Reviewing and Editing. **Muhammad Zuber:** Writing- Reviewing and Editing, Formal analysis, Supervision. **Hamna Nasir:** Writing-Reviewing and Editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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