Hindawi
Journal of Chemistry
Volume 2021, Article ID 6562687, 14 pages
https://doi.org/10.1155/2021/6562687

Review Article

Plant-Extract-Mediated Synthesis of Metal Nanoparticles

Yunhui Bao, Jian He, Ke Song, Jie Guo, Xianwu Zhou, and Shima Liu

Key Laboratory of Hunan Forest Products and Chemical Industry Engineering, Jishou University, Zhangjiajie, Hunan 427000, China

Correspondence should be addressed to Shima Liu; liushima@jsu.edu.cn

Received 11 June 2021; Accepted 30 July 2021; Published 19 August 2021

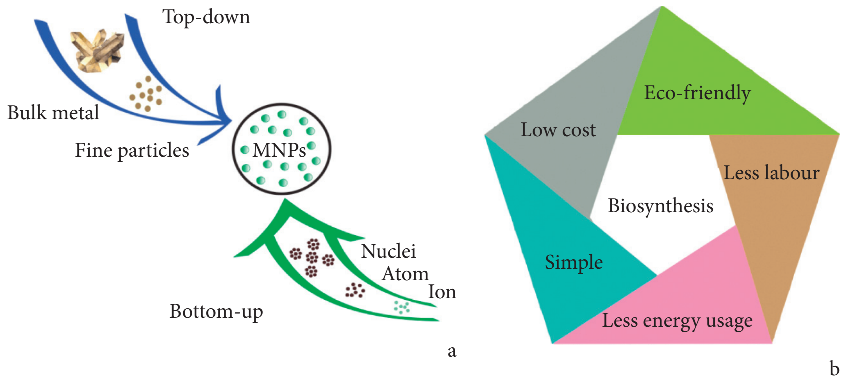
Academic Editor: Dario Pasini

Metal nanoparticles (MNPs) have been widely used in several fields including catalysis, bioengineering, photoelectricity, antibacterial, anticancer, and medical imaging due to their unique physical and chemical properties. In the traditional synthesis method of MNPs, toxic chemicals are generally used as reducing agents and stabilizing agents, which is fussy to operate and extremely environment unfriendly. Based on this, the development of an environment-friendly synthesis method of MNPs has recently attracted great attention. The use of plant extracts as reductants and stabilizers to synthesize MNPs has the advantages of low cost, environmental friendliness, sustainability, and ease of operation. Besides, the as-synthesized MNPs are nontoxic, more stable, and more uniform in size than the counterparts prepared by the traditional method. Thus, green preparation methods have become a research hotspot in the field of MNPs synthesis. In this review, recent advances in green synthesis of MNPs using plant extracts as reductants and stabilizers have been systematically summarized. In addition, the insights into the potential applications and future development for MNPs prepared by using plant extracts have been provided.

1. Introduction

Many areas of research including medicine, catalysis, photoelectricity, and industrial manufacture have been revolutionized by nanotechnology. It is estimated that the industrial production of nanomaterials had reached 58,000 tons per year in 2020 [1]. Metal nanoparticles (MNPs) have been widely used in catalysis, bioengineering, electronics, optoelectronics, medicine, sensing, and information storage [2, 3] due to unique physicochemical and biological properties of MNPs such as high electrical conductivity, thermal conductivity, chemical stability, high catalytic activity, and biomedically related antimicrobial and anticancer activities [4, 5]. The synthesis of MNPs usually includes "Top-down" and "Bottom-up" approaches (Figure 1(a)). The "Top-down" approach fabricates MNPs from the corresponding bulk metallic materials by various physical or chemical methods (e.g., mechanical grinding, laser ablation, and thermal decomposition) to achieve size reduction [6]. The "Top-down" preparation method often requires high pressure, temperature, and expensive specialized equipment, as well as usually introduces defects in the surface structure of MNPs. Since the physicochemical properties of nanoparticles are highly dependent on their surface structure [7], the application of MNPs prepared by the "Top-down" method is greatly limited.

In the "Bottom-up" synthesis, MNPs are formed by stacking the corresponding metal atoms [8], which mainly includes chemical synthesis and biosynthesis. Generally, chemical synthesis uses polyvinylpyrrolidone, alkyl mercaptan, thioanthracenol, dimethylformamide, or Tween 80 as the stabilizer and sodium borohydride, hydrazine hydrate, or formaldehyde as the reducing agent to synthesize MNPs [9]. This route inevitably uses toxic chemicals and is, therefore, extremely environment unfriendly. In the process of preparing MNPs with traditional chemical reducing agents, some stabilizers are usually added to maintain the stability of MNPs due to the fierce reduction reaction. The chemical reducing agents used in this process are generally expensive, toxic, and dangerous, which can bring a variety of hazards to the experimenters and the environment [10]. Thus, a green reducing agent featured with mild reaction, low cost, and easy operation and acting as a stabilizer agent is highly desirable. The biosynthesis method mainly uses



(a) (b)

Figure 1: Two synthesis strategies of metal nanoparticles (a) and advantages of biosynthesis methods of MNPs (b).

microorganisms, plants, or extracts of both as a stabilizer and reducing agent, respectively, to synthesize MNPs. The feasibility of this route mainly lies in the presence of bioactive molecules such as proteins, amino acids, or polysaccharides contained in microorganisms and active ingredients such as terpenoids, phenols, alkaloids, flavonoids, quinines, or tannins contained in plants, which not only have antibacterial and antioxidant ability but also reduce metal salts and stabilize nanoparticles [11]. Biosynthesis methods are low energy consuming, cheap, and very environment friendly (Figure 1(b)) compared to chemical synthesis methods [12, 13]. However, the microbial-based synthesis, which has the disadvantages of time consumption on cultivation of bacteria or fungi, high cost, and being prone to biosafety problems, is generally not applied [14]. In contrast, the plant-mediated synthesis method of MNPs featured with many advantages including being more rapid, cheap, and simpler operation with more abundant resources [11] and has, therefore, received widespread attention from researchers around the world. In addition, plant extracts not only have good biocompatibility, biodegradability, environmental friendliness, and low cost but also provide a stable protective layer for MNPs and, therefore, prevent MNPs from aggregation [15]. Herein, the recent studies on the synthesis of MNPs using plant extracts has been systematically summarized, with emphasis on several MNPs such as nanogold, silver, copper, platinum, and palladium. Moreover, the applications of related MNPs have also been briefly introduced, which may provide reference and inspiration for future research on the green synthesis of MNPs.

2. Plant-Extract-Mediated Synthesis of Metal Nanoparticles

2.1. Synthesis of Gold Nanoparticles. In the field of nanomaterial research, gold nanoparticles (AuNPs) are of great interest due to their stability, size controllability, biocompatibility, high adsorption capacity, and high catalytic activity [16]. AuNPs have a wide range of applications in medicine [17], drug and gene delivery [18], biosensors [19], tomography [20], photocatalysis [21], environmental sensing [22] and water purification [23]. Among the most commonly used "Bottom-up" synthesis strategies (Figure 1(a)), the metal ions are firstly reduced to metal atoms, the metal atoms are then self-assembled to form nuclei, and subsequently, the metal nuclei continue to grow to form MNPs, which includes the processes of coprecipitation, sol-gel, and atomic condensation [24, 25]. The currently used chemical synthesis of AuNPs usually involves toxic chemicals that adsorb on the surface of AuNPs, limiting their applications in fields such as biology and medicine. Therefore, there is an urgent need for novel green and efficient synthetic methods to replace toxic chemical synthesis. In this context, plant-extract-mediated AuNP synthesis has aroused numerous interests since it can produce AuNPs efficiently and the as-prepared AuNPs have better biocompatibility without carrying toxic chemicals [26].

AuNPs were synthesized using leaf extracts; Guo et al. [27] prepared AuNPs by reducing chloroauric acid ($HAuCl_4$) using ethanol extracts of dried powder of vine tea leaves. They also studied the effects of reaction conditions such as temperature, pH, and extract dosage on the physicochemical properties of AuNPs and found that alkaline conditions or excess vine tea extracts led to agglomeration of AuNPs; higher temperature was more favorable for the synthesis of small-sized AuNPs, and AuNPs were more stable at low temperature. Tao et al. [28] reported that spherical and highly crystalline AuNPs with particle size between 20–60 nm were prepared by reducing $HAuCl_4$ using aqueous extracts of aloe vera leaves, and under the protection of the extracts, the AuNPs were less prone to agglomeration and oxidation and had good stability.

AuNPs were synthesized using flower extracts; Ghosh et al. [29] found that the aqueous extracts of *Gnidia glauca* flowers could reduce $HAuCl_4$ and synthesize AuNPs within 20 min. The resulting AuNPs contained spherical, triangular, and hexagonal shapes, with sizes mainly around 10 nm. It was also found that the AuNPs had a significant catalytic effect on the synthesis of 4-aminophenol by reduction of 4-nitrophenol with $NaBH_4$. Zangeneh and Zangeneh [30] reduced $HAuCl_4 \cdot 3H_2O$ with water extracts from *Hibiscus sabdariffa* flowers and obtained spherical AuNPs with a particle size of 15–45 nm. Interestingly, the as-synthesized AuNPs could significantly reduce proinflammatory cytokines and enhance anti-inflammatory cytokines. In addition, AuNPs showed no significant cytotoxicity to endothelial cells, which was similar to daunorubicin.

AuNPs were synthesized using extracts of fruits or fruit shells; Baldea et al. [31] studied the feasibility of AuNPs synthesis using the water extracts from *Cornus mas* fruit and the biological effects of the as-obtained AuNPs. It was found that $HAuCl_4$ could be reduced to AuNPs at pH = 7.5 and AuNPs had selective toxicity to hypertrophic keratinocytes and could induce their death. The AuNPs showed good biocompatibility to normal gingival fibroblasts and had the potential to be used in the treatment of diseases related to oral dysplasia. Sathishkumar et al. [32] reported that nanogold was prepared by reduction of $HAuCl_4$ using aqueous extracts of *Couroupita guianensis* fruits at pH = 7, at 70°C, with 1 mM substrate and 5 mL of fruit extracts when reacting for 60 min. The AuNPs obtained had an average size of 26 ± 11 nm, was negatively charged, nonagglomerated, and covered by a layer of polyphenolic substances. In addition, it was found that the as-prepared AuNPs have good antioxidant and hemocompatibility properties. Chen [33] prepared hydrophilic AuNPs with sizes of 9–23 nm using mangosteen polyphenols from the aqueous extracts of *Garcinia mangostana* L. pericarp as reducing and stabilizing agents, respectively, and found that decreasing the concentration of the extracts resulted in various forms of AuNPs.

AuNPs were synthesized using root extracts; Sutan et al. [45] showed that ethanol extracts of *Aconitum toxicum* Reichenb roots reduced with $HAuCl_4$ for three hours at room temperature could be used to prepare AuNPs with a size of 9–15 nm. Meanwhile, the total polyphenol content of the extracts was measured to be 1.49%, and the aconitine content was measured to be 4.891 mg/mL. The antioxidant activity of the AuNPs was measured to be between 78% and 84.32%. Gonzalez-Ballesteros et al. [46] found when the water extracts of an *Ulva intestinalis* L. was used to reduce chlorauric acid for 4 hours under the condition of pH = 6.65, AuNPs were synthesized. The average diameter and the average zeta potential of AuNPs were 17.8 ± 2.7 nm and -22.30 ± 0.24 mV, respectively. The biocompatibility of AuNPs was systematically studied, and the results showed that AuNPs had good biocompatibility and low hemolytic toxicity and could induce cell proliferation. Similarly, Jacob et al. [47] showed that water extracts from *Brassica oleracea* var. *capitata* plants could reduce $HAuCl_4$ to prepare AuNPs, and the diameter of AuNPs was related to the pH value of the reaction medium, reaction time, and initial reactant concentration.

The AuNPs were synthesized using extracts from whole plants; Lee et al. [48] extracted the active ingredient in *Ocimum sanctum* with four solvents of different polarities, namely, water, *n*-butanol, chloroform, and *n*-hexane, and used the extracts to reduce $HAuCl_4$ to produce AuNPs. They found that the AuNPs synthesized from the water extracts were mainly thin flakes with various shapes and sizes along with neat edges, while the AuNPs synthesized from *n*-butanol extracts were mainly spherical small particles of about 20 nm in size and nanosheets of about 1 μm in size; the AuNPs synthesized from chloroform extracts were mainly nanosheets with rough edges; the AuNPs synthesized from hexane extracts were mainly nanospheres of less than 10 nm.

In conclusion, researchers have prepared AuNPs using flavonoids, polyphenols and amino acids from leaves, flowers, seeds, roots, and fruits of plants as reducing and stabilizing agents and $HAuCl_4$ as the precursor (Table 1) to achieve the green synthesis of AuNPs. Many researchers also investigated the effects of extracts concentration, reaction temperature, pH, and reaction time on the morphology of AuNPs. The applications of AuNPs prepared *via* green synthesis mainly focused on detection and antibacterial and catalytic degradation of certain colored dyes. In the future, the synthesis of AuNPs using plant extracts has great potential, and it is worthwhile to further explore the synthesis mechanism to achieve precise and controllable AuNPs morphology or to synthesize AuNPs on the surface of other materials by in situ reduction to form multifaceted composites, which are all research directions worthy of investment.

2.2. Synthesis of Silver Nanoparticles. Silver nanoparticles (AgNPs), an important product in the field of nanotechnology, are one of the most widely used nanoparticles in the biomedical field [49]. Owing to their unique chemical stability, good electrical conductivity and catalytic properties, and particularly outstanding antimicrobial properties [50], AgNPs have been used in a large number of applications including biomolecular detection, drug delivery, food production, antimicrobial, and agricultural fields [51]. In particular, AgNPs have become one of the most promising materials for fighting the threat of drug-resistant bacteria due to their excellent antimicrobial properties [52]. The use of AgNPs synthesized from plant extracts is more beneficial for AgNPs to exploit their value in biomedical and other fields thanks to their low toxicity and biocompatibility [5, 53].

AgNPs were synthesized using leaf extracts; Pang et al. [54] found that AgNPs could be prepared from the extracts of *Youngia japonica* leaves, and the suitable reaction conditions were 60 mL of yellow quail leaf extracts (material ratio 15 g/L), 10 mL of $AgNO_3$ (0.005 mol/L), a reaction temperature of 60°C, and a reaction time for 40 min; the average particle size of the resulting AgNPs was 20 nm, and most of them were spherical; they had a significant suppressing effect on the bacteria isolated from the stem ends of cut lilies and are expected to be applied to the freshness treatment of cut flowers after the reaction. Wang et al. [55] obtained AgNPs by reducing silver nitrate with the aqueous extracts of green tea, and the obtained AgNPs were spherical with a particle size of 30–40 nm. Meanwhile, the optimal conditions for the preparation of AgNPs by this system were determined by orthogonal experiments: $AgNO_3$ concentration 0.08 mol/L, green tea extracts 0.0125 g/mL, reaction temperature 40°C, and time 2 h.

AgNPs were synthesized using extracts of the fruits; Jiang et al. [67] prepared AgNPs by reducing silver nitrate using aqueous and ethanolic extracts of hawthorn fruits as

Table 1: Representative examples for the use of plant extracts for AuNP synthesis.

Plant	Part	Extractant	Precursor	Size (nm)	Reference
Butea monosperma	Leaf	Water	$HAuCl_4$	10–100	[34]
Pelargonium graveolens	Leaf	Water	$HAuCl_4$	20–40	[35]
Salix alba	Leaf	Water	$HAuCl_4{\cdot}3H_2O$	50–80	[36]
Guazuma ulmifolia L.	Bark	Water	$HAuCl_4{\cdot}3H_2O$	20–25	[37]
Mimusops elengi	Bark	Ethanol	$HAuCl_4$	9–14	[38]
Nerium oleander	Bark	Methanol	$HAuCl_4$	20–40	[39]
Rubia cordifolia	Fruit	Ethanol	$HAuCl_4$	5–20	[40]
Litsea cubeba	Fruit	Water	$HAuCl_4{\cdot}3H_2O$	8–18	[41]
Piper longum	Fruit	Water	$HAuCl_4$	20–200	[42]
Hibiscus sabdariffa	Flower	Water	$HAuCl_4{\cdot}3H_2O$	15–45	[30]
Coleus forskohlii	Root	Water	$HAuCl_4$	5–18	[43]
Stachys lavandulifolia	Overground part	Water	$HAuCl_4$	34–80	[44]

reducing and stabilizing agents, respectively. A comparative study revealed that the AgNPs synthesized from the aqueous extracts were smaller and more homogeneous and had higher antibacterial activity. Kumar et al. [62] examined the feasibility of synthesizing AgNPs from extracts of *Eugenia stipitata* McVaugh fruits, and the results proved feasible. The as-prepared AgNPs were spherical in shape and 15–45 nm in size and had good antioxidant effects; furthermore, infrared spectroscopy demonstrated that the synthesis of AgNPs was associated with malic acid, citric acid, and carotenoids in the extracts.

AgNPs were synthesized using extracts of the bark or tubers; Rohaizad et al. [64] used aqueous extracts of the *Catharanthus roseus* bark as the raw material to reduce silver nitrate *via* green synthesis and produced AgNPs in situ on the surface of graphene oxide (GO). The resulting AgNPs were mostly spherical with particle sizes ranging from 1 to 26 nm, and the AgNPs-GO composites showed good adsorption effect on methylene blue dye. Liu et al. [68] used 70% ethanol extracts of ginger as a reducing agent for the green synthesis of AgNPs, and the AgNPs obtained were face-centered cubic structures with spherical shape and a particle size of 5–30 nm and had good thermal stability and antibacterial effect.

AgNPs were synthesized using the root or whole plant extracts; Sun et al. [69] found that rhubarb root extracts could be used to prepare AgNPs with an average particle size of 40.3 nm; it was also found that rhubarb root extracts improved not only the stability of AgNPs but also the antibacterial ability of AgNPs. Yousaf et al. [70] used water, ethanol, and methanol extracts of *Achillea millefolium* L. separately to reduce silver nitrate for 24 h. The particle sizes of the synthesized AgNPs were 20.77 nm, 18.53 nm, and 14.27 nm, respectively. AgNPs showed good inhibitory effect and strong free-radical scavenging activity against a variety of Gram-negative/-positive bacteria. Khoshnamvand et al. [58] found that the aqueous extracts of the *Chlorella vulgaris* could reduce silver nitrate 60°C and the resulting AgNPs were mostly spherical in shape with a size of 28.95 ± 10.17 nm and zeta potential of -23.23 ± 0.75 mV. In addition, the AgNPs were found to be biotoxic to *Chlorella vulgaris* in a dose-dependent manner; however, the natural organic matter (Suwannee River humic acid) could effectively reduce their biotoxicity.

In summary, similar to the commonly used synthesis methods of MNPs and their application (Figure 2), when using plant extracts to produce AgNPs, water was mainly used as the extraction solvent, partly ethanol or methanol solution, all silver salts used were silver nitrate (Table 2), and the reaction time was mostly longer than 1 h. The resulting AgNPs were mainly used in the antibacterial field. Therefore, it is of great importance to explore to further shorten the reaction time for synthesizing AgNPs in subsequent studies and to investigate the in vivo and in vitro toxicity of such AgNPs more systematically in order to better exploit their antibacterial properties, especially anti-drug-resistant bacteria, which is of great significance.

2.3. Synthesis of Copper Nanoparticles. Copper is an important micronutrient and an essential component of many proteins and enzymes. Copper nanoparticles (CuNPs) have the advantages of easy availability, low cost, excellent electrical conductivity, good catalytic properties, and surface-enhanced Raman scattering activity [71], which enable it to be widely used in biomedicine, gas sensing, textile coating, batteries, solar energy conversion, and high-temperature superconductors [72]. The synthesis of CuNPs using plant extracts is of great value for research because of its low cytotoxicity, economic prospect, environmental friendliness, biocompatibility, good antioxidant properties, and antibacterial activity [73].

CuNPs were synthesized using leaf extracts; Das et al. [74] found that copper sulfate pentahydrate could be reduced using 50% ethanol extracts of *Moringa oleifera* leaves at 60°C for 3 h to obtain amorphous CuNPs of size 35.8–49.2 nm. The as-prepared CuNPs exhibited antioxidant, antibacterial, and antifungal activities. Rajeshkumar et al. [75] first used aqueous extracts of *Cissus arnotiana* leaves to reduce copper sulfate for 4 h at room temperature and obtained spherical CuNPs of size 60–90 nm. The resulting CuNPs exhibited antibacterial and antioxidant activities. Copper sulfate was reduced (refluxed at 80°C for 16 h) with aqueous extracts of *Allium Eriophyllum* leaves by Zhao et al. [76] to obtain spherical CuNPs with a size of 25–35 nm. The as-synthesized CuNPs featured with good stability, noncytotoxicity, antioxidant activity, antibacterial activity, and promoting wound healing.

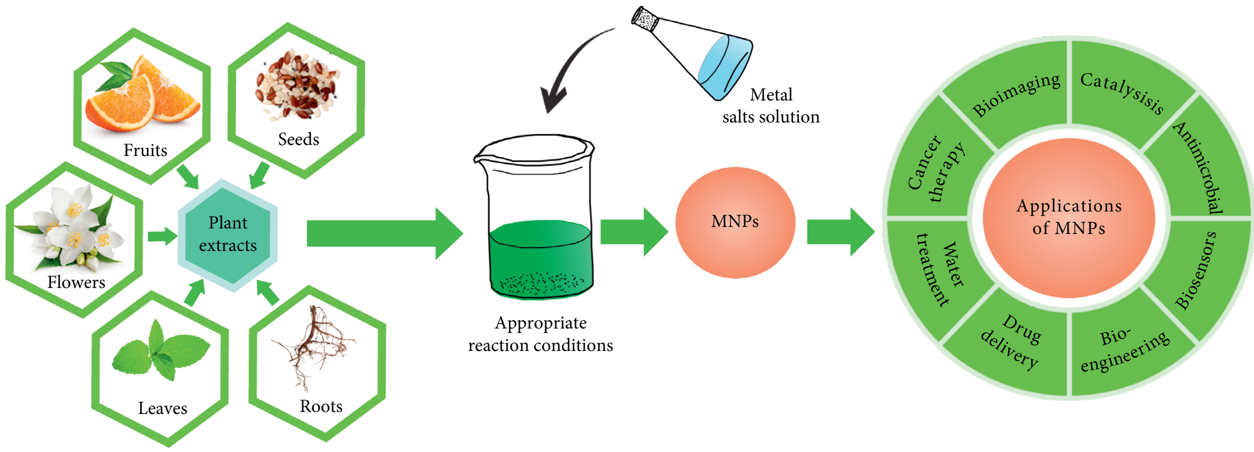


Figure 2: Schematic of the synthesis and application of metal nanoparticles by using plant extracts.

Table 2: Representative examples for the use of plant extracts for AgNP synthesis.

Plant	Part	Extractant	Precursor	Size (nm)	Reference
Lotus garcinii	Leaf	Water	$AgNO_3$	7–20	[56]
Morinda citrifolia	Leaf	Methanol	$AgNO_3$	10–100	[57]
Allium fistulosum	Leaf	Water	$AgNO_3$	28.95 ± 10.17	[58]
Moringa oleifera	Leaf	Water	$AgNO_3$	15–25	[59]
Ocimum basilicum	Seed	Water	$AgNO_3$	~13.82	[60]
Prunus mume	Fruit	Water	$AgNO_3$	~30	[61]
Eugenia stipitata McVaugh	Fruit	Water	$AgNO_3$	15–45	[62]
Garcinia mangostana L	Fruit	Water	$AgNO_3$	~23	[63]
Aconitum toxicum Reichenb.	Root	96% ethanol	$AgNO_3$	53–67	[45]
Catharanthus roseus	Bark	Water	$AgNO_3$	1–26	[64]
Ulva armoricana	Whole plant	Water	$AgNO_3$	~215	[65]
Ulva lactuca L.	Whole plant	Water	$AgNO_3$	31 ± 8	[66]

CuNPs were synthesized using flower or bark extracts; Dinesh et al. [77] applied aqueous extracts of *Hibiscus rosa-sinensis* flowers to reduce copper acetate monohydrate and obtained square CuNPs with the size of 0.115–1.1 μm in a 30 min reaction assisted by acoustic waves. Meanwhile, it was found that the CuNPs could generate free radicals to catalyze the degradation of two drugs, 5-fluorouracil and lovastatin. Pinto et al. [78] used different concentrations of aqueous extracts of *Eucalyptus globulus* bark to reduce copper chloride dihydrate in oleamide, oleic acid, and ethanol systems, respectively, for 2 h at 120°C to produce CuNPs. Meanwhile, the phytoactive components of the extracts were attached to CuNPs, rendering CuNPs with better antioxidant and conductive effects. The CuNPs showed no sign of copper oxide phase after two weeks of storage.

CuNPs were synthesized using fruit or seed extracts; Khani et al. [86] reported the reduction of copper sulfate using aqueous extracts of dried *Ziziphus spina-christi* (L.) Willd. fruit powder associated with starch as a stabilizer, to produce spherical CuNPs with a particle size of 5–20 nm. The resulting CuNPs showed an inhibitory activity against *Escherichia coli* and *Staphylococcus aureus* in a concentration-dependent manner. In addition, the CuNPs were found to have good adsorption effect on crystalline violet. Sajadi et al. [84] used the aqueous extracts of *Silybum marianum* L. seeds to react with both ferric chloride hexahydrate and copper chloride dihydrate to produce CuNPs-Fe_3O_4 composites at 60°C, which are of sizes 8.5–60 nm and good stability (>2 months). The possible synthesis mechanism is shown in Figure 3. In terms of application, CuNPs-Fe_3O_4 was found to be effective in catalyzing the reduction of nitroaromatics and was recyclable and reusable (more than five times).

Researchers have used plant flower, leaf, seed, fruit, and bark extracts to reduce certain copper salts (e.g., copper acetate monohydrate, copper chloride, copper chloride dihydrate, copper sulfate, copper nitrate trihydrate, and copper sulfate pentahydrate) to prepare CuNPs (Table 3). The resulting CuNPs are mainly used for detection, antibacterial, antioxidant, degradation of organic dyes, and mitigation of cytotoxicity of certain drugs. In addition, some CuNPs prepared *via* green synthesis using plant extracts were found to have better antibacterial effects and biocompatibility compared with CuNPs synthesized *via* traditional methods; since copper itself is a trace element required by the human body, it is of great practical value and significance to broaden the application of green-synthesized CuNPs for antibacterial and drug toxicity mitigation in the human body in future studies.

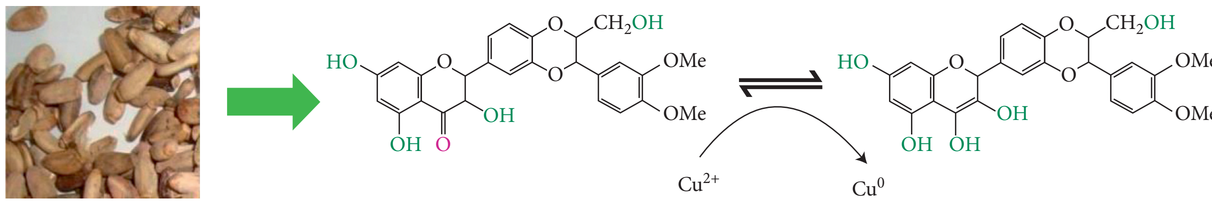


Figure 3: Mechanism of CuNP synthesis using *Silybum marianum* L. seed extracts [84].

Table 3: Representative examples for the use of plant extracts for CuNP synthesis.

Plant	Part	Extractant	Precursor	Size	Reference
Allium eriophyllum Boiss.	Leaf	Water	$CuSO_4$	25–35 nm	[76]
Artemisia haussknechtii	Leaf	Water	$CuSO_4$	35.36 ± 44.4 nm	[79]
Achillea biebersteinii	Leaf	Water	$Cu(NO_3)_2{\cdot}3H_2O$	16.8 nm	[80]
Ocimum sanctum	Leaf	Water	$CuSO_4{\cdot}5H_2O$	50–70 nm	[81]
Hibiscus rosa-sinensis	Flower	Water	$Cu(CH_3COO)_2{\cdot}H_2O$	0.115–1.1 μm	[77]
Quisqualis indica	Flower	Water	$Cu(CH_3COO)_2{\cdot}H_2O$	39.3 ± 5.45 nm	[82]
Anthemis xylopoda	Flower	Water	$CuCl_2$	10.2–45 nm	[83]
Silybum marianum L.	Seed	Water	$Cu(CH_3COO)_2{\cdot}H_2O$	8.5–60 nm	[84]
P. granatum	Seed	Water	$CuCl_2$	40–80 nm	[85]
Ziziphus spina-christi (L.) Willd.	Fruit	Water	$CuSO_4$	5–20 nm	[86]
Calotropis procera L.	Latex	Water	$Cu(CH_3COO)_2{\cdot}H_2O$	15 ± 1.7 nm	[87]
Protoparmeliopsis muralis	Whole plant	Water	$CuSO_4$	253.97 ± 57.2 nm	[88]

2.4. Synthesis of Platinum Nanoparticles. Currently, transition metal nanoparticles, especially platinum nanoparticles (PtNPs), are extensively studied. PtNPs have attracted widespread attention due to their applications in the automotive industry, chemical industry, and biomedicine [89]. Traditional physical and chemical synthesis methods of PtNPs are not only energy intensive and require harsh conditions but also inevitably require the use of toxic solvents or reducing agents, which are highly unfriendly to the environment [90]. PtNPs prepared by biosynthesis are preferred for various applications due to their good biocompatibility and ecofriendliness. Therefore, the development of facile and environment friendly methods for the synthesis of PtNPs is not only important for the development and utilization of PtNPs but also caters to the trend of green chemistry [91].

PtNPs were synthesized using extracts of fruits or peels; Sundar et al. [105] found that PtNPs could be produced by reducing H_2PtCl_6 using aqueous extracts of *Sapinduss mukkorossi* fruits. In addition, it was found that this PtNP-modified electrode could be applied to detect single nanoparticle collision. Sahin et al. [106] fabricated PtNPs by reducing $PtCl_4$ with ethanol extracts of pomegranate peel in the first place and then demonstrated that PtNPs induced apoptosis in human breast cancer cells (MCF-7) through cytotoxicity assay. Nishanthi et al. [63] reported that the aqueous extracts of *Garcinia mangostana* fruit peel could reduce $H_2PtCl_6{\cdot}6H_2O$ at 80°C for 20 min to produce PtNPs. The antibacterial activity of PtNPs was also evaluated against human pathogenic bacteria before and after the combination of PtNPs with antibiotics.

PtNPs were synthesized using extracts of leaves or whole plants; Henam et al. [107] reported that the aqueous extracts of *Mimosa pudica* leaves were used to reduce H_2PtCl_6 to prepare ultra-small-size PtNPs, and the average particle size of the resulting PtNPs was about 1.4 nm. In addition, it was found that the PtNPs had good catalytic effect on the decomposition of hydrogen peroxide. Dobrucka et al. [108] investigated the feasibility of preparing PtNPs by reduction of K_2PtCl_6 with aqueous extracts of *Fumariae herba* and found that the resulting PtNPs showed subhexagonal and pentagonal morphology with an average particle size of about 30 nm and had good catalytic properties for the reduction of methylene blue and crystalline violet. Furthermore, there are some examples of the synthesis of PtNPs using plant extracts which are summarized in Table 4.

It can be seen that the synthesis of PtNPs using plant extracts provides a diversity of precursors of platinum source, mainly including $H_2PtCl_6{\cdot}6H_2O$, K_2PtCl_6, $PtCl_4$, Na_2PtC_4, H_2PtCl_2. The temperature of the synthesis reaction is generally high (greater than 80°C), and the resulting PtNPs are small, most of which do not exceed 10 nm. The applications are mainly focused on antibacterial, anticancer, and catalytic degradation of organic dyes. However, there are still many challenges in developing green synthetic PtNPs for nanomedicine applications, and more in vitro and animal experiments are needed to investigate the clearance mechanism, antioxidant activity, and long-term effects of PtNPs on the immune system.

2.5. Synthesis of Palladium Nanoparticles. In recent years, palladium nanoparticles (PdNPs) have been discovered to have numerous applications in organocatalysis, hydrogen production, supercapacitors, and biosensors owing to their high specific surface area and high surface energy [109, 110]. Various traditional methods including sol-gel, rapid precipitation, acoustochemical, electrochemical, solid-phase

Table 4: Representative examples for the use of plant extracts for PtNP synthesis.

Plant	Part	Extractant	Precursor	Size (nm)	Reference
Ocimum sanctum	Leaf	Water	$H_2PtCl_6{\cdot}6H_2O$	~23	[92]
Costus speciosus	Leaf	95% ethanol	Platinum 2,4-pentanedionate	10–50	[93]
Bacopa monnier	Leaf	Water	H_2PtCl_6	5–20	[94]
Azadirachta indica	Leaf	Water	$H_2PtCl_6{\cdot}6H_2O$	5–50	[95]
Mentha piperita	Leaf	Water	H_2PtCl_6	~54.3	[96]
Quercus Glauca	Leaf	Water	$H_2PtCl_6{\cdot}6H_2O$	5–15	[97]
Coffea Arabica	Seed	Water	H_2PtCl_6	~2	[98]
Nigella sativa L.	Seed	70% ethanol	$PtCl_4$	1–6	[99]
Terminalia chebula	Fruit	Water	H_2PtCl_6	<4	[100]
Garcinia mangostana L.	Fruit	Water	$H_2PtCl_6{\cdot}6H_2O$	20–25	[63]
Taraxacum laevigatum	Whole plant	Water	H_2PtCl_6	2–7	[101]
Padina gymnospora	Whole plant	Water	H_2PtCl_6	5–50	[102]
Cacumen Platycladi	Whole plant	Water	Na_2PtCl_4	1.6–3.2	[103]
Dioscorea bulbifera	Tuber	Water	$H_2PtCl_6{\cdot}6H_2O$	2–5	[104]

reaction, microwave radiation, and alcohol-thermal synthesis have been developed for synthesizing Pd nanoparticles [111]. However, these methods suffer from some shortcomings such as harsh reaction conditions, high reaction temperature, long reaction time, expensive raw materials, and environmental damage [112]. Therefore, the green synthesis method based on using plant extracts for the synthesis of PdNPs has received much attention and has been widely used for the synthesis of PdNPs.

PdNPs were synthesized using leaf extracts; Kanchana et al. [113] used aqueous extracts of *Solanum trilobatum* leaves to reduce $PdCl_2$ at room temperature for 24 h to obtain PdNPs. The particle size of the resulting PdNPs was mainly in the range of 60–70 nm. Nasrollahzadeh et al. [114] found that the aqueous extracts of *Hippophae rhamnoides* leaves could reduce $PdCl_2$ to prepare PdNPs with a spherical particle size of 2.5–14 nm. Also, this PdNP has ideal catalytic activity as a multiphase catalyst in the Suzuki–Miyaura coupling reaction. The rGO-*T. spicata* complex was obtained by attaching the water extracts of *Thymbra spicata* leaves to the surface of GO, as reported by Veisi et al. [115]. Afterwards, Na_2PdCl_4 was added to the mixture and stirred at 100°C for 12 h, in which Na_2PdCl_4 was reduced to PdNPs to obtain the PdNPs/rGO-*T. spicata* nanocomposite. At the same time, the as-obtained complex can effectively catalyze the cyanation of halides.

PdNPs were synthesized using extracts of fruits or peels; Nasrollahzadeh et al. [116] used aqueous extracts of barberry fruits as reducing agents to synthesize PdNPs in situ on the surface of reduced graphene oxide (rGO). The PdNP-rGO complexes were produced by vigorous stirring at 75°C for 10 h. When determining its catalytic performance, it is revealed that PdNP-rGO can be used as an efficient multiphase catalyst for the reduction of nitroaromatics by sodium borohydride without significant activity loss and high product yields after 5 cycles. Bankar et al. [117] used aqueous extracts of banana peel at 80°C for 3 min in an aqueous solution to reduce $PdCl_2$ into PdNPs. The average particle size of the resulting PdNPs was 50 nm. The carboxyl, amino, and hydroxyl groups in the extracts were presumed by infrared spectroscopy to have a possible role in the reduction of $PdCl_2$.

PdNPs were synthesized using extracts of the bark or whole plant; Mishra et al. [118] used aqueous extracts of the *Ulmus davidiana* bark as a reducing agent to reduce $PdCl_2$ at 60°C for 2 h with ultrasonic assistance to synthesize PdNPs. Sathishkumar et al. [119] showed that *Cinnamon zeylanicum* bark extracts could reduce $PdCl_2$ at 30°C for 72 h and, thus, obtain PdNPs. The resulting PdNPs were spherical with particle size ranging from 15 to 20 nm, and it was also found that the pH value of the reaction did not affect the shape of the nanoparticles but affected their size and dispersibility. Momeni et al. [120] used *Sargassum bovinum* aqueous extracts to reduce $PdCl_2$. The color of the reaction system changed from yellow to dark brown indicating the formation of PdNPs, which had a particle size of 5–10 nm and good stability (>5 months) and could effectively catalyze the electrochemical reduction of hydrogen peroxide. In the work of Khan et al. [121], using extracts of *Pulicaria glutinosa*, PdNPs were prepared by reducing $PdCl_2$ at 90°C with stirring for 2 h. The color of the solution changed from yellow to dark brown indicating the formation of PdNPs, and the particle size of the resulting PdNPs was 20–25 nm. It was found that the PdNPs had good catalytic activity in the Suzuki reaction for the synthesis of biphenyl from bromobenzene.

As reported in the review paper, we can find that the corresponding extracts originate from several parts of plants, such as leaves, fruits, fruit shells, bark, bark, and roots (Table 5). The extraction solvent is mainly water, and the precursor of PdNPs is mainly $PdCl_2$. The particle size of the resulting PdNPs is generally no more than 50 nm, which is mainly used in the field of catalysis in organic chemistry, especially the Suzuki–Miyaura coupling reaction, and can be reused many times. In future investigation, the synthesis of PdNPs with more homogeneous particle size and controllable shape, as well as the investigation of the specific reaction mechanism and the exact amount of extracts demand, remain scientifically significant and challenging research directions.

2.6. Other Metal Nanoparticles. In addition to gold, silver, copper, platinum, and palladium nanoparticles, green synthesis of MNPs using plant extracts has been also applied to prepare other metal nanoparticles. Lin et al. [127] reported

Table 5: Representative examples for the use of plant extracts for PdNP synthesis.

Plant	Part	Extractant	Precursor	Size (nm)	Reference
Artemisia annua	Leaf	Water	$PdCl_2$	20–30	[122]
Camellia sinensis	Leaf	Water	$PdCl_2$	5–8	[123]
Euphorbia thymifolia L.	Leaf	Water	$PdCl_2$	20–30	[124]
Euphorbia granulate	Leaf	Water	$PdCl_2$	25–35	[125]
Thymbra spicata	Leaf	Water	Na_2PdCl_4	10–15	[115]
Solanum trilobatum	Leaf	Water	$PdCl_2$	60–100	[113]
Hippophae rhamnoides	Leaf	Water	$PdCl_2$	2.5~14	[114]
Berberis vulgaris	Fruit	Water	$PdCl_2$	~18	[116]
Ulmus davidiana	Bark	Water	$PdCl_2$	~5	[118]
Cinnamon zeylanicum	Bark	Water	$PdCl_2$	15–20	[119]
Sargassum bovinum	Whole plant	Water	$PdCl_2$	5–10	[120]
Salvia hydrangea	Whole plant	70% ethanol	$Pd(NO_3)_2$	<10	[126]

that iron nanoparticles were successfully prepared by reducing ferric chloride using aqueous extracts of *Hizikia fusiformis*, and the resulting iron nanoparticles were spherical in shape with a particle size of about 17–40 nm. In terms of application, the nanoparticles were found to be capable of removing 92.76% of Cr(VI) from water. Ituen et al. [128] used the ethanol extracts of *Allium cepa* to reduce $Ni(NO_3)_2$ (50°C, 45 min) to synthesize nanonickel. The as-obtained nanonickel possessed highly crystalline and spherical appearance with a particle size of 39.5–53.1 nm as well as possessed an average zeta potential of 46.4 mV. It is found that the nanonickel can effectively alleviate the corrosion of steel. Elango et al. [129] used methanolic extracts of *Cocos nucifera* shells as reducing and stabilizing agents to fabricate nanonickel by reducing nickel acetate at 60°C. The resulting nanonickel was square in shape with an average particle size of 47 nm and had good stability. The nanonickel was also found to have insecticidal activity against the agricultural pest *Callasobruchus maculates.* 98.92% of Cu(II), 98.16% of Cr(III), and 93.39% of Ni(II) in the solution were removed, as reported by Vaseghi et al. [130], by using aqueous extracts of *Eryngium campestre* (wild spurge) leaves under the conditions of room temperature, pH = 7, and 3.5 min. The established synthesis method is green and nontoxic based on turning waste into treasure and has broad application prospects.

Apart from these documented MNPs, nanoalloys, such as Fe-Ni, Ag-Pd, Au-Pd, Fe-Pd, and Au-Ag alloys, have been also successfully prepared by green synthesis methods based on using plant extracts [131, 132]. In addition, green synthesis of nanometal oxides by plant extracts has been recently reported.

3. Chemical Mechanisms of Metal Nanoparticle Synthesis Using Plant Extracts

Various active ingredients including alkaloids, phenols, terpenoids, quinines, amides, flavonoids, proteins, and alcohols exist in plant extracts, among which reducing active ingredients such as flavonoids and phenols can reduce some metal cations to MNPs and, at the same time, act as stabilizers to prevent the aggregation of MNPs, thus playing a key role in the green synthesis of MNPs [15, 133]. It was found that the preparation of MNPs using plant extracts can be generally divided into the following three phases: the reduction phase, growth phase, and termination phase. In the reduction stage, the reducing phytoactives reduce metal ions to zero-valent metal atoms by electron transfer. Subsequently, the zero-valent metal atoms grow by aggregation into nanometallic particles with various shapes (linear, rod shaped, triangular, hexagonal, or cubic) in the growth stage. Finally, the phytoactive components with antioxidant properties are enriched around the MNPs to maintain the stability of MNPs in the termination stage [77, 134].

Sajadi et al. [84] utilized polyphenolic substances, such as flavonolignans, from *Silybum marianum* L. seed extracts to reduce copper ions to CuNPs and their own structure was transformed from keto to enol, as shown in Figure 3. Yu et al. [135] used nanocellulose to synthesize AgNPs, where positively charged silver ions were attracted to negatively charged carboxyl and hydroxyl groups on nanocellulose. At 80°C, the silver ions were reduced by the hydroxyl groups, which themselves were oxidized to aldehyde groups. Jigyasa and Rajput [136] used polyphenols (rutin/curcumin) to synthesize AgNPs and speculated that rutin/curcumin may have obtained AgNPs by reducing silver ions through carbonyl or phenolic hydroxyl groups. Wang et al. [15] used starch to synthesize AgNPs and found that the abundant hydroxyl and carboxyl groups on the linear chain of starch interacted with silver ions and, thus, the hydroxyl groups reduced the silver ions to AgNPs. Moreover, it was found that the prepared AgNPs were stable owing to the passivated surface of AgNPs and surrounded by negatively charged carboxyl groups.

Plant extracts possess not only reducing but also antioxidant properties and serve as a reducing agent to prepare MNPs while acting as a stabilizer to protect them from oxidation. Veisi et al. [137] found that flavonoids, tannins, and phenolic compounds attached to the surface of AgNPs to keep them stable through electronic interactions. The presence of active components with antioxidant properties in plant extracts that reduce copper ions and synchronously maintain the stability of copper nanoparticles was reported by Nasrollahzadeh et al. [138].

4. Conclusions and Prospect

In summary, this review discussed the recent progress on the green synthesis of MNPs using plant extracts, focusing on the synthesis of several commonly used MNPs such as nanogold, silver, copper, platinum, and palladium. The booming development of green chemistry and nanotechnology has promoted the exploitation of green synthetic methods for synthesizing nanomaterials *via* plants and microorganisms. The green synthesis of MNPs has recently received much attention in sustainable chemistry. The plant-extract-mediated method for the preparation of MNPs has the advantages of low cost, nontoxicity, easy scale-up, and environmental friendliness, which are highly conducive to sustainable nanoscience development. Particularly, the as-synthesized MNPs have a wide range of applications in the fields of catalysis, medicine, water treatment, antibacterial, anticancer, bioengineering, sensors, and medical imaging. Importantly, the synthesis reaction does not involve any toxic chemical reagents and the resulting MNPs are not contaminated with toxic substances, thus being of special value in biomedical applications where nontoxicity is strictly required. In addition, plant extracts contain some unique compounds that help to improve the synthesis efficiency and increase the stability of MNPs.

Despite the significant progress made in this field, there are still a number of issues that need to be addressed. For instance, despite the great potential of MNPs prepared *via* plant-extract-mediated methods, the specific synthetic process parameters still need to be optimized. Meanwhile, the relevant synthetic mechanisms need to be further elucidated, and the lack of understanding of the chemical components involved in the synthesis and stabilization of MNPs remains a great challenge for researchers. Moreover, the manner in which active molecules in the extracts attach to the surface of MNPs and the determination of the real molecular active groups in the molecules need to be further investigated. Furthermore, with the exponential growth of MNP applications, the accumulation of these nanoparticles in the environment is a concern, and there is a need to focus on the in vivo toxicity of these MNPs and the long-term effects on humans, animals, and the environment. Further investigation of these issues is expected to facilitate us to better utilize this green synthesis method for the development and progress of human society.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

SL acknowledges the Hunan Provincial Natural Science Foundation of China (No. 2021JJ40439). KS acknowledges the National Natural Science Foundation of China (No. 32060326). XZ acknowledges the Research Foundation of Hunan Provincial Education Department (No. 19C1525).

References

[1] R. A. Kudgus, K. Giri, R. Bhattacharya et al., "Intrinsic therapeutic applications of noble metal nanoparticles: past, present and future," *Chemical Society Reviews*, vol. 41, no. 7, pp. 2943–2970, 2012.

[2] S. E. Skrabalak, L. Au, X. Lu, X. Li, and Y. Xia, "Gold nanocages for cancer detection and treatment," *Nanomedicine*, vol. 2, no. 5, pp. 657–668, 2007.

[3] E. Antolini, "Palladium in fuel cell catalysis," *Energy & Environmental Science*, vol. 2, no. 9, pp. 915–931, 2009.

[4] F. T. Minhas, G. Arslan, I. H. Gubbuk et al., "Evaluation of antibacterial properties on polysulfone composite membranes using synthesized biogenic silver nanoparticles with *Ulva compressa* (L.) *Kütz.* and *Cladophora glomerata* (L.) *Kütz.* extracts," *International Journal of Biological Macromolecules*, vol. 107, pp. 157–165, 2018.

[5] P. Dauthal and M. Mukhopadhyay, "Noble metal nanoparticles: plant-mediated synthesis, mechanistic aspects of synthesis, and applications," *Industrial & Engineering Chemistry Research*, vol. 55, no. 36, pp. 9557–9577, 2016.

[6] M. A. Meyers, A. Mishra, and D. J. Benson, "Mechanical properties of nanocrystalline materials," *Progress in Materials Science*, vol. 51, no. 4, pp. 427–556, 2006.

[7] K. N. Thakkar, S. S. Mhatre, and R. Y. Parikh, "Biological synthesis of metallic nanoparticles," *Nanomedicine: Nanotechnology, Biology and Medicine*, vol. 6, no. 2, pp. 257–262, 2010.

[8] P. Mukherjee, A. Ahmad, D. Mandal et al., "Fungus-mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis," *Nano Letters*, vol. 1, no. 10, pp. 515–519, 2001.

[9] H. Lee, A. K. R. Lytton-Jean, Y. Chen et al., "Molecularly self-assembled nucleic acid nanoparticles for targeted in vivo siRNA delivery," *Nature Nanotechnology*, vol. 7, no. 6, pp. 389–393, 2012.

[10] D. Nath and P. Banerjee, "Green nanotechnology-a new hope for medical biology," *Environmental Toxicology and Pharmacology*, vol. 36, no. 3, pp. 997–1014, 2013.

[11] K. B. Narayanan and N. Sakthivel, "Green synthesis of biogenic metal nanoparticles by terrestrial and aquatic phototrophic and heterotrophic eukaryotes and biocompatible agents," *Advances in Colloid and Interface Science*, vol. 169, no. 2, pp. 59–79, 2011.

[12] P. Raveendran, J. Fu, and S. L. Wallen, "Completely "green" synthesis and stabilization of metal nanoparticles," *Journal of the American Chemical Society*, vol. 125, no. 46, pp. 13940-13941, 2003.

[13] S. A. Akintelu, S. C. Olugbeko, F. A. Folorunso, A. K. Oyebamiji, and A. S. Folorunso, "Characterization and pharmacological efficacy of silver nanoparticles biosynthesized using the bark extract of *Garcinia Kola*," *Journal of Chemistry*, vol. 2020, pp. 2876019–2876025, 2020.

[14] V. Kumar and S. K. Yadav, "Plant-mediated synthesis of silver and gold nanoparticles and their applications," *Journal of Chemical Technology & Biotechnology*, vol. 84, no. 2, pp. 151–157, 2009.

[15] X. Wang, L. Yuan, H. Deng, and Z. Zhang, "Structural characterization and stability study of green synthesized starch stabilized silver nanoparticles loaded with

isoorientin," *Food Chemistry*, vol. 338, pp. 127807–127809, 2021.

[16] R. Guo, Y. Song, G. Wang, and R. W. Murray, "Does core size matter in the kinetics of ligand exchanges of monolayer-protected Au clusters?" *Journal of the American Chemical Society*, vol. 127, no. 8, pp. 2752–2757, 2005.

[17] D. Pissuwan, C. H. Cortie, S. M. Valenzuela, and M. B. Cortie, "Functionalised gold nanoparticles for controlling pathogenic bacteria," *Trends in Biotechnology*, vol. 28, no. 4, pp. 207–213, 2010.

[18] P. Ghosh, G. Han, M. De, C. Kim, and V. Rotello, "Gold nanoparticles in delivery applications," *Advanced Drug Delivery Reviews*, vol. 60, no. 11, pp. 1307–1315, 2008.

[19] S. Singh, D. V. S. Jain, and M. L. Singla, "Sol-gel based composite of gold nanoparticles as matix for tyrosinase for amperometric catechol biosensor," *Sensors and Actuators B: Chemical*, vol. 182, pp. 161–169, 2013.

[20] H. Liu, Y. Xu, S. Wen et al., "Facile hydrothermal synthesis of low generation dendrimer-stabilized gold nanoparticles for in vivo computed tomography imaging applications," *Polymer Chemistry*, vol. 4, no. 6, pp. 1788–1795, 2013.

[21] B. Paul, B. Bhuyan, D. Dhar Purkayastha, M. Dey, and S. S. Dhar, "Green synthesis of gold nanoparticles using *Pogestemon benghalensis* (B) O. *Ktz*. leaf extract and studies of their photocatalytic activity in degradation of methylene blue," *Materials Letters*, vol. 148, pp. 37–40, 2015.

[22] K. Saha, S. S. Agasti, C. Kim, X. Li, and V. M. Rotello, "Gold nanoparticles in chemical and biological sensing," *Chemical Reviews*, vol. 112, no. 5, pp. 2739–2779, 2012.

[23] T. Pradeep and Anshup, "Noble metal nanoparticles for water purification: a critical review," *Thin Solid Films*, vol. 517, no. 24, pp. 6441–6478, 2009.

[24] M. Yadi, E. Mostafavi, B. Saleh et al., "Current developments in green synthesis of metallic nanoparticles using plant extracts: a review," *Artificial cells, nanomedicine, and biotechnology*, vol. 46, pp. S336–S343, 2018.

[25] L. Castillo-Henríquez, K. Alfaro-Aguilar, J. Ugalde-Álvarez, L. Vega-Fernández, G. Montes de Oca-Vásquez, and J. R. Vega-Baudrit, "Green synthesis of gold and silver nanoparticles from plant extracts and their possible applications as antimicrobial agents in the agricultural area," *Nanomaterials*, vol. 10, no. 9, pp. 1763–1786, 2020.

[26] S. K. Nune, N. Chanda, R. Shukla et al., "Green nanotechnology from tea: phytochemicals in tea as building blocks for production of biocompatible gold nanoparticles," *Journal of Materials Chemistry*, vol. 19, no. 19, pp. 2912–2920, 2009.

[27] Q. Guo, Z. Fu, C. Dong et al., "Biosynthesis of gold nanoparticles using vine tea powder extracts," *Chinese Journal of Applied Chemistry*, vol. 31, no. 7, pp. 841–846, 2014.

[28] J. Tao, Z. Fu, C. Dong, X. Wang, and X. Yang, "Green synthesis and characterization of monodisperse gold nanoparticles using aloe vera leaf extract," *Rare Metal Materials and Engineering*, vol. 48, no. 11, pp. 3470–3475, 2019.

[29] S. Ghosh, S. Patil, M. Ahire et al., "*Gnidia glauca* flower extract mediated synthesis of gold nanoparticles and evaluation of its chemocatalytic potential," *Journal of Nanobiotechnology*, vol. 10, no. 1, pp. 17–25, 2012.

[30] M. M. Zangeneh and A. Zangeneh, "Novel green synthesis of *Hibiscus sabdariffa* flower extract conjugated gold nanoparticles with excellent anti-acute myeloid leukemia effect in comparison to daunorubicin in a leukemic rodent model," *Applied Organometallic Chemistry*, vol. 34, no. 1, pp. 5271–5283, 2020.

[31] I. Baldea, A. Florea, D. Olteanu et al., "Effects of silver and gold nanoparticles phytosynthesized with *Cornus mas* extract on oral dysplastic human cells," *Nanomedicine*, vol. 15, no. 1, pp. 55–75, 2020.

[32] G. Sathishkumar, P. K. Jha, V. Vignesh et al., "Cannonball fruit (*Couroupita guianensis*, Aubl.) extract mediated synthesis of gold nanoparticles and evaluation of its antioxidant activity," *Journal of Molecular Liquids*, vol. 215, pp. 229–236, 2016.

[33] L. Chen, "Study on biosynthesis and spectral property of gold nanoparticles in the extracts of mangosteen (*Garcinia mangostana* L) pericarp," *Chemical Research and Application*, vol. 26, no. 1, pp. 74–80, 2014.

[34] S. Patra, S. Mukherjee, A. K. Barui, A. Ganguly, B. Sreedhar, and C. R. Patra, "Green synthesis, characterization of gold and silver nanoparticles and their potential application for cancer therapeutics," *Materials Science and Engineering: C*, vol. 53, pp. 298–309, 2015.

[35] S. S. Shankar, A. Ahmad, R. Pasricha, and M. Sastry, "Bioreduction of chloroaurate ions by geranium leaves and its endophytic fungus yields gold nanoparticles of different shapes," *Journal of Materials Chemistry*, vol. 13, no. 7, pp. 1822–1826, 2003.

[36] N. U. Islam, K. Jalil, M. Shahid et al., "Green synthesis and biological activities of gold nanoparticles functionalized with Salix alba," *Arabian Journal of Chemistry*, vol. 12, no. 8, pp. 2914–2925, 2019.

[37] V. Karthika, A. Arumugam, K. Gopinath et al., "Guazuma ulmifolia bark-synthesized Ag, Au and Ag/Au alloy nanoparticles: photocatalytic potential, DNA/protein interactions, anticancer activity and toxicity against 14 species of microbial pathogens," *Journal of Photochemistry and Photobiology B: Biology*, vol. 167, pp. 189–199, 2017.

[38] R. Majumdar, B. G. Bag, and P. Ghosh, "Mimusops elengi bark extract mediated green synthesis of gold nanoparticles and study of its catalytic activity," *Applied Nanoscience*, vol. 6, no. 4, pp. 521–528, 2016.

[39] A. C. Barai, K. Paul, A. Dey et al., "Green synthesis of Nerium oleander-conjugated gold nanoparticles and study of its in vitro anticancer activity on MCF-7 cell lines and catalytic activity," *Nano Convergence*, vol. 5, no. 1, pp. 10–18, 2018.

[40] A. K. Singh, Y. B. Tripathi, N. Pandey, D. P. Singh, D. Tripathi, and O. N. Srivastava, "Enhanced anti-lipopolysaccharide (LPS) induced changes in macrophage functions by *Rubia cordifolia* (RC) embedded with Au nanoparticles," *Free Radical Biology and Medicine*, vol. 65, pp. 217–223, 2013.

[41] D. Van-Dat, T. Anh Tai, N. Thanh-Danh et al., "Biosynthesis of gold nanoparticles using *Litsea cubeba* fruit extract for catalytic reduction of 4-nitrophenol," *Journal of Nanomaterials*, vol. 2020, Article ID 4548790, 10 pages, 2020.

[42] J. R. Nakkala, R. Mata, and S. R. Sadras, "The antioxidant and catalytic activities of green synthesized gold nanoparticles from *Piper longum* fruit extract," *Process Safety and Environmental Protection*, vol. 100, pp. 288–294, 2016.

[43] S. Naraginti, P. L. Kumari, R. K. Das, A. Sivakumar, S. H. Patil, and V. V. Andhalkar, "Amelioration of excision wounds by topical application of green synthesized, formulated silver and gold nanoparticles in albino Wistar rats," *Materials Science and Engineering: C*, vol. 62, pp. 293–300, 2016.

[44] P. Khademi-Azandehi and J. Moghaddam, "Green synthesis, characterization and physiological stability of gold nanoparticles from *Stachys lavandulifolia* Vahl extract," *Particuology*, vol. 19, pp. 22–26, 2015.

[45] N. A. Sutan, D. S. Manolescu, I. Fierascu et al., "Phytosynthesis of gold and silver nanoparticles enhance in vitro antioxidant and mitostimulatory activity of *Aconitum toxicum* Reichenb. rhizomes alcoholic extracts," *Materials Science and Engineering: C*, vol. 93, pp. 746–758, 2018.

[46] N. González-Ballesteros, L. Diego-González, M. Lastra-Valdor et al., "Immunostimulant and biocompatible gold and silver nanoparticles synthesized using the *Ulva intestinalis* L. aqueous extract," *Journal of Materials Chemistry B*, vol. 7, no. 30, pp. 4677–4691, 2019.

[47] J. Jacob, T. Mukherjee, and S. Kapoor, "A simple approach for facile synthesis of Ag, anisotropic Au and bimetallic (Ag/Au) nanoparticles using cruciferous vegetable extracts," *Materials Science and Engineering: C*, vol. 32, no. 7, pp. 1827–1834, 2012.

[48] S. Y. Lee, S. Krishnamurthy, C.-W. Cho, and Y.-S. Yun, "Biosynthesis of gold nanoparticles using *Ocimum sanctum* extracts by solvents with different polarity," *ACS Sustainable Chemistry & Engineering*, vol. 4, no. 5, pp. 2651–2659, 2016.

[49] O. V. Kharissova, H. V. R. Dias, B. I. Kharisov, B. O. Pérez, and V. M. J. Pérez, "The greener synthesis of nanoparticles," *Trends in Biotechnology*, vol. 31, no. 4, pp. 240–248, 2013.

[50] S. Jain and M. S. Mehata, "Medicinal plant leaf extract and pure flavonoid mediated green synthesis of silver nanoparticles and their enhanced antibacterial property," *Scientific Reports*, vol. 7, no. 1, pp. 15867–15879, 2017.

[51] M. Ghorbanpour, A. H. Khaltabadi Farahani, and J. Hadian, "Potential toxicity of nano-graphene oxide on callus cell of *Plantago major* L. under polyethylene glycol-induced dehydration," *Ecotoxicology and Environmental Safety*, vol. 148, pp. 910–922, 2018.

[52] A. Panacek, L. Kvítek, R. Prucek et al., "Silver colloid nanoparticles: synthesis, characterization, and their antibacterial activity," *Journal of Physical Chemistry B*, vol. 110, no. 33, pp. 16248–16253, 2006.

[53] V. T. Nguyen, "Sunlight-driven synthesis of silver nanoparticles using pomelo peel extract and antibacterial testing," *Journal of Chemistry*, vol. 2020, Article ID 6407081, 9 pages, 2020.

[54] Z. Pang, H. Li, J. Liu, G. Yu, and S. He, "Nano-silver preparation using leaf extracts of *Youngia japonica* and its in hibitory effects on growth of bacteria from cut lily stemends," *Northern Horticulture*, vol. 14, pp. 103–109, 2020.

[55] Y. Wang, H. Chen, and R. Lan, "Preparation of nano-silver with green tea extract," *Environmental Science & Technology*, vol. 36, no. 12, pp. 122–125, 2013.

[56] M. Maham, M. Nasrollahzadeh, S. M. Sajadi, and M. Nekoei, "Biosynthesis of Ag/reduced graphene oxide/Fe_3O_4 using *Lotus garcinii* leaf extract and its application as a recyclable nanocatalyst for the reduction of 4-nitrophenol and organic dyes," *Journal of Colloid and Interface Science*, vol. 497, pp. 33–42, 2017.

[57] G. N. Rajivgandhi, M. Maruthupandy, J.-L. Li et al., "Photocatalytic reduction and anti-bacterial activity of biosynthesized silver nanoparticles against multi drug resistant *Staphylococcus saprophyticus* BDUMS 5 (MN310601)," *Materials Science and Engineering: C*, vol. 114, pp. 111024–111036, 2020.

[58] M. Khoshnamvand, S. Ashtiani, Y. Chen, and J. Liu, "Impacts of organic matter on the toxicity of biosynthesized silver nanoparticles to green microalgae *Chlorella vulgaris*," *Environmental Research*, vol. 185, pp. 109433–109440, 2020.

[59] H. M. Ibrahim, S. Zaghloul, M. Hashem, and A. El-Shafei, "A green approach to improve the antibacterial properties of cellulose based fabrics using *Moringa oleifera* extract in presence of silver nanoparticles," *Cellulose*, vol. 28, no. 1, pp. 549–564, 2021.

[60] S. Pirtarighat, M. Ghannadnia, and S. Baghshahi, "Biosynthesis of silver nanoparticles using *Ocimum basilicum* cultured under controlled conditions for bactericidal application," *Materials Science and Engineering: C*, vol. 98, pp. 250–255, 2019.

[61] T. N. J. I. Edison, R. Atchudan, N. Karthik, J. Balaji, D. Xiong, and Y. R. Lee, "Catalytic degradation of organic dyes using green synthesized N-doped carbon supported silver nanoparticles," *Fuel*, vol. 280, pp. 118682–118688, 2020.

[62] B. Kumar, K. Smita, A. Debut, and L. Cumbal, "Extracellular green synthesis of silver nanoparticles using Amazonian fruit Araza (*Eugenia stipitata* McVaugh)," *Transactions of Nonferrous Metals Society of China*, vol. 26, no. 9, pp. 2363–2371, 2016.

[63] R. Nishanthi, S. Malathi, S John Paul, and P. Palani, "Green synthesis and characterization of bioinspired silver, gold and platinum nanoparticles and evaluation of their synergistic antibacterial activity after combining with different classes of antibiotics," *Materials Science and Engineering: C*, vol. 96, pp. 693–707, 2019.

[64] A. Rohaizad, S. Shahabuddin, M. M. Shahid et al., "Green synthesis of silver nanoparticles from *Catharanthus roseus* dried bark extract deposited on graphene oxide for effective adsorption of methylene blue dye," *Journal of Environmental Chemical Engineering*, vol. 8, no. 4, pp. 103955–103964, 2020.

[65] A. Massironi, A. Morelli, L. Grassi et al., "Ulvan as novel reducing and stabilizing agent from renewable algal biomass: application to green synthesis of silver nanoparticles," *Carbohydrate Polymers*, vol. 203, pp. 310–321, 2019.

[66] N. González-Ballesteros, M. C. Rodríguez-Argüelles, S. Prado-López et al., "Macroalgae to nanoparticles: study of *Ulva lactuca* L. role in biosynthesis of gold and silver nanoparticles and of their cytotoxicity on colon cancer cell lines," *Materials Science and Engineering: C*, vol. 97, pp. 498–509, 2019.

[67] Y. Jiang, F. Li, C. Liu et al., "Biosynthezied silver nanopaticles using hawthorn fruit extract and their antibacterial activitiy against four common aquatic pathogens," *Oceanologia Et Limnologia Sinica*, vol. 47, no. 1, pp. 253–260, 2016.

[68] C. Liu, L. Wang, H. Xu et al., "Antibacterial study of silver nanoparticles biosynthesized with ginger extract," *Journal of Food Science and Biotechnology*, vol. 36, no. 6, pp. 590–597, 2017.

[69] C. Sun, S. Chen, and C. Yu, "Rhubarb extract prepares nano silver antibacterial material forms and efficacy," *Chinese Archives of Traditional Chinese Medicine*, vol. 35, no. 5, pp. 1070–1073, 2017.

[70] H. Yousaf, A. Mehmood, K. S. Ahmad, and M. Raffi, "Green synthesis of silver nanoparticles and their applications as an alternative antibacterial and antioxidant agents," *Materials Science and Engineering: C*, vol. 112, pp. 110901–110907, 2020.

[71] S. Chandra, A. Kumar, and P. K. Tomar, "Synthesis and characterization of copper nanoparticles by reducing agent," *Journal of Saudi Chemical Society*, vol. 18, no. 2, pp. 149–153, 2014.

[72] Y. Chen, D. Wang, X. Zhu, X. Zheng, and L. Feng, "Long-term effects of copper nanoparticles on wastewater biological nutrient removal and N_2O generation in the activated sludge process," *Environmental Science & Technology*, vol. 46, no. 22, pp. 12452–12458, 2012.

[73] M. I. Din, F. Arshad, Z. Hussain, and M. Mukhtar, "Green adeptness in the synthesis and stabilization of copper nanoparticles: catalytic, antibacterial, cytotoxicity, and antioxidant activities," *Nanoscale Research Letters*, vol. 12, no. 1, pp. 638–652, 2017.

[74] P. E. Das, I. A. Abu-Yousef, A. F. Majdalawieh, S. Narasimhan, and P. Poltronieri, "Green synthesis of encapsulated copper nanoparticles using a hydroalcoholic extract of *Moringa oleifera* leaves and assessment of their antioxidant and antimicrobial activities," *Molecules*, vol. 25, no. 3, pp. 555–571, 2020.

[75] S. Rajeshkumar, S. Menon, S. Tambuwala et al., "Antibacterial and antioxidant potential of biosynthesized copper nanoparticles mediated through *Cissus arnotiana* plant extract," *Journal of Photochemistry and Photobiology B: Biology*, vol. 197, pp. 111531–111536, 2019.

[76] H. Zhao, H. Su, A. Ahmeda et al., "Biosynthesis of copper nanoparticles using *Allium eriophyllum* Boiss leaf aqueous extract; characterization and analysis of their antimicrobial and cutaneous wound-healing potentials," *Applied Organometallic Chemistry*, 2020.

[77] G. K. Dinesh, M. Pramod, and S. Chakma, "Sonochemical synthesis of amphoteric Cu^0-nanoparticles using *Hibiscus rosa-sinensis* extract and their applications for degradation of 5-fluorouracil and lovastatin drugs," *Journal of Hazardous Materials*, vol. 399, pp. 123035–123048, 2020.

[78] R. J. B. Pinto, J. M. F. Lucas, F. M. Silva et al., "Bio-based synthesis of oxidation resistant copper nanowires using an aqueous plant extract," *Journal of Cleaner Production*, vol. 221, pp. 122–131, 2019.

[79] M. Alavi and N. Karimi, "Characterization, antibacterial, total antioxidant, scavenging, reducing power and ion chelating activities of green synthesized silver, copper and titanium dioxide nanoparticles using *Artemisia haussknechtii* leaf extract," *Artificial cells, nanomedicine, and biotechnology*, vol. 46, no. 8, pp. 2066–2081, 2018.

[80] G. Wang, A. Ahmeda, Z. Malek, S. Mansooridara, A. Zangeneh, and M. M. Zangeneh, "Chemical characterization and therapeutic properties of *Achillea biebersteinii* leaf aqueous extract synthesized copper nanoparticles against methamphetamine-induced cell death in PC12: a study in the nanotechnology and neurology fields," *Applied Organometallic Chemistry*, vol. 34, no. 4, pp. 5488–5501, 2020.

[81] V. Sadanand, N. Rajini, A. Varada Rajulu, and B. Satyanarayana, "Preparation of cellulose composites with in situ generated copper nanoparticles using leaf extract and their properties," *Carbohydrate Polymers*, vol. 150, pp. 32–39, 2016.

[82] R. Mukhopadhyay, J. Kazi, and M. C. Debnath, "Synthesis and characterization of copper nanoparticles stabilized with *Quisqualis indica* extract: evaluation of its cytotoxicity and apoptosis in B16F10 melanoma cells," *Biomedicine & Pharmacotherapy*, vol. 97, pp. 1373–1385, 2018.

[83] M. Nasrollahzadeh, S. M. Sajadi, and A. Hatamifard, "Anthemis xylopoda flowers aqueous extract assisted in situ green synthesis of Cu nanoparticles supported on natural natrolite zeolite for *N*-formylation of amines at room temperature under environmentally benign reaction conditions," *Journal of Colloid and Interface Science*, vol. 460, pp. 146–153, 2015.

[84] S. M. Sajadi, M. Nasrollahzadeh, and M. Maham, "Aqueous extract from seeds of *Silybum marianum* L. as a green material for preparation of the Cu/Fe_3O_4 nanoparticles: a magnetically recoverable and reusable catalyst for the reduction of nitroarenes," *Journal of Colloid and Interface Science*, vol. 469, pp. 93–98, 2016.

[85] N. Nazar, I. Bibi, S. Kamal et al., "Cu nanoparticles synthesis using biological molecule of *P. granatum* seeds extract as reducing and capping agent: growth mechanism and photocatalytic activity," *International Journal of Biological Macromolecules*, vol. 106, pp. 1203–1210, 2018.

[86] R. Khani, B. Roostaei, G. Bagherzade, and M. Moudi, "Green synthesis of copper nanoparticles by fruit extract of *Ziziphus spina-christi* (L.) Willd.: application for adsorption of triphenylmethane dye and antibacterial assay," *Journal of Molecular Liquids*, vol. 255, pp. 541–549, 2018.

[87] S. Harne, A. Sharma, M. Dhaygude, S. Joglekar, K. Kodam, and M. Hudlikar, "Novel route for rapid biosynthesis of copper nanoparticles using aqueous extract of *Calotropis procera* L. latex and their cytotoxicity on tumor cells," *Colloids and Surfaces B: Biointerfaces*, vol. 95, pp. 284–288, 2012.

[88] M. Alavi, N. Karimi, and T. Valadbeigi, "Antibacterial, antibiofilm, antiquorum sensing, antimotility, and antioxidant activities of green fabricated Ag, Cu, TiO_2, ZnO, and Fe_3O_4 NPs via *Protoparmeliopsis muralis* lichen aqueous extract against multi-drug-resistant bacteria," *ACS Biomaterials Science & Engineering*, vol. 5, no. 9, pp. 4228–4243, 2019.

[89] D. Pedone, M. Moglianetti, E. De Luca, G. Bardi, and P. P. Pompa, "Platinum nanoparticles in nanobiomedicine," *Chemical Society Reviews*, vol. 46, no. 16, pp. 4951–4975, 2017.

[90] P. Mukherjee, M. Roy, B. P. Mandal et al., "Green synthesis of highly stabilized nanocrystalline silver particles by a non-pathogenic and agriculturally important fungus *T. asperellum*," *Nanotechnology*, vol. 19, no. 7, pp. 075103–075110, 2008.

[91] P. Dauthal and M. Mukhopadhyay, "Biofabrication, characterization, and possible bio-reduction mechanism of platinum nanoparticles mediated by agro-industrial waste and their catalytic activity," *Journal of Industrial and Engineering Chemistry*, vol. 22, pp. 185–191, 2015.

[92] C. Soundarrajan, A. Sankari, P. Dhandapani et al., "Rapid biological synthesis of platinum nanoparticles using *Ocimum sanctum* for water electrolysis applications," *Bioprocess and Biosystems Engineering*, vol. 35, no. 5, pp. 827–833, 2012.

[93] C. Surya, N. A. Arul John, V. Pandiyan et al., "Costus speciosus leaf extract assisted CS-Pt-TiO_2 composites: synthesis, characterization and their bio and photocatalytic applications," *Journal of Molecular Structure*, vol. 1195, pp. 787–795, 2019.

[94] J. Nellore, C. Pauline, and K. Amarnath, "Bacopa monnieri phytochemicals mediated synthesis of platinum nanoparticles and its neurorescue effect on 1-methyl 4-phenyl 1,2,3,6 tetrahydropyridine-induced experimental parkinsonism in zebrafish," *Journal of neurodegenerative diseases*, vol. 2013, Article ID 972391, 8 pages, 2013.

[95] A. Thirumurugan, P. Aswitha, C. Kiruthika, S. Nagarajan, and A. N. Christy, "Green synthesis of platinum nanoparticles using *Azadirachta indica*-an eco-friendly approach," *Materials Letters*, vol. 170, pp. 175–178, 2016.

[96] C. Yang, M. Wang, J. Zhou, and Q. Chi, "Bio-synthesis of peppermint leaf extract polyphenols capped nano-platinum and their in-vitro cytotoxicity towards colon cancer cell lines (HCT 116)," *Materials Science and Engineering: C*, vol. 77, pp. 1012–1016, 2017.

[97] R. Karthik, R. Sasikumar, S.-M. Chen et al., "Green synthesis of platinum nanoparticles using *Quercus Glauca* extract and

its electrochemical oxidation of hydrazine in water samples," *International Journal of Electrochemical Science*, vol. 11, no. 10, pp. 8245–8255, 2016.

[98] N. K. R. Bogireddy, U. Pal, M. K. Kumar, J. M. Domínguez, L. M. Gomez, and V. Agarwal, "Green fabrication of 2D platinum superstructures and their high catalytic activity for mitigation of organic pollutants," *Catalysis Today*, vol. 360, pp. 185–193, 2021.

[99] A. Aygun, F. Gülbagca, L. Y. Ozer et al., "Biogenic platinum nanoparticles using black cumin seed and their potential usage as antimicrobial and anticancer agent," *Journal of Pharmaceutical and Biomedical Analysis*, vol. 179, pp. 112961–112968, 2020.

[100] K. M. Kumar, B. K. Mandal, and S. K. Tammina, "Green synthesis of nano platinum using naturally occurring polyphenols," *RSC Advances*, vol. 3, no. 12, pp. 4033–4039, 2013.

[101] K. Tahir, S. Nazir, A. Ahmad et al., "Facile and green synthesis of phytochemicals capped platinum nanoparticles and in vitro their superior antibacterial activity," *Journal of Photochemistry and Photobiology B: Biology*, vol. 166, pp. 246–251, 2017.

[102] V. S. Ramkumar, A. Pugazhendhi, S. Prakash et al., "Synthesis of platinum nanoparticles using seaweed *Padina gymnospora* and their catalytic activity as PVP/PtNPs nanocomposite towards biological applications," *Biomedicine & Pharmacotherapy*, vol. 92, pp. 479–490, 2017.

[103] B. Zheng, T. Kong, X. Jing et al., "Plant-mediated synthesis of platinum nanoparticles and its bioreductive mechanism," *Journal of Colloid and Interface Science*, vol. 396, pp. 138–145, 2013.

[104] S. Ghosh, R. Nitnavare, A. Dewle et al., "Novel platinum-palladium bimetallic nanoparticles synthesized by *Dioscorea bulbifera*: anticancer and antioxidant activities," *International Journal of Nanomedicine*, vol. 10, pp. 7477–7490, 2015.

[105] S. Sundar, K. J. Kim, and S. J. Kwon, "Observation of single nanoparticle collisions with green synthesized Pt, Au, and Ag nanoparticles using electrocatalytic signal amplification method," *Nanomaterials*, vol. 9, no. 12, pp. 1695–1707, 2019.

[106] B. Sahin, A. Aygun, H. Gunduz et al., "Cytotoxic effects of platinum nanoparticles obtained from pomegranate extract by the green synthesis method on the MCF-7 cell line," *Colloids and Surfaces B-Biointerfaces*, vol. 163, pp. 119–124, 2018.

[107] P. S. Henam, F. D. Heikham, and S. D. Henam, "Sustainable synthesis of ultrasmall biogenic platinum nanoparticles for selective aqueous phase conversion of glucose and effective hydrogen peroxide decomposition," *Industrial & Engineering Chemistry Research*, vol. 57, no. 14, pp. 5190–5194, 2018.

[108] R. Dobrucka, "Biofabrication of platinum nanoparticles using *Fumariae herba* extract and their catalytic properties," *Saudi Journal of Biological Sciences*, vol. 26, no. 1, pp. 31–37, 2019.

[109] Q. Zeng, J.-S. Cheng, X.-F. Liu, H.-T. Bai, and J.-H. Jiang, "Palladium nanoparticle/chitosan-grafted graphene nanocomposites for construction of a glucose biosensor," *Biosensors and Bioelectronics*, vol. 26, no. 8, pp. 3456–3463, 2011.

[110] F. Gobal and M. Faraji, "Electrodeposited polyaniline on Pd-loaded TiO_2 nanotubes as active material for electrochemical supercapacitor," *Journal of Electroanalytical Chemistry*, vol. 691, pp. 51–56, 2013.

[111] B. Khodadadi, M. Bordbar, and A. Yeganeh-Faal, "Optical, structural, and photocatalytic properties of Cd-doped ZnO powders prepared via sol-gel method," *Journal of Sol-Gel Science and Technology*, vol. 77, no. 3, pp. 521–527, 2016.

[112] G. Zhan, J. Huang, M. Du et al., "Green synthesis of Au-Pd bimetallic nanoparticles: single-step bioreduction method with plant extract," *Materials Letters*, vol. 65, no. 19-20, pp. 2989–2991, 2011.

[113] A. Kanchana, S. Devarajan, and S. R. Ayyappan, "Green synthesis and characterization of palladium nanoparticles and its conjugates from *Solanum trilobatum* leaf extract," *Nano-Micro Letters*, vol. 2, no. 3, pp. 169–176, 2010.

[114] M. Nasrollahzadeh, S. M. Sajadi, and M. Maham, "Green synthesis of palladium nanoparticles using *Hippophae rhamnoides Linn* leaf extract and their catalytic activity for the Suzuki-Miyaura coupling in water," *Journal of Molecular Catalysis A: Chemical*, vol. 396, pp. 297–303, 2015.

[115] H. Veisi, T. Tamoradi, B. Karmakar, P. Mohammadi, and S. Hemmati, "In situ biogenic synthesis of Pd nanoparticles over reduced graphene oxide by using a plant extract (*Thymbra spicata*) and its catalytic evaluation towards cyanation of aryl halides," *Materials Science & Engineering C-Materials for Biological Applications*, vol. 104, Article ID 109919, 2019.

[116] M. Nasrollahzadeh, S. Mohammad Sajadi, A. Rostami-Vartooni, M. Alizadeh, and M. Bagherzadeh, "Green synthesis of the Pd nanoparticles supported on reduced graphene oxide using barberry fruit extract and its application as a recyclable and heterogeneous catalyst for the reduction of nitroarenes," *Journal of Colloid and Interface Science*, vol. 466, pp. 360–368, 2016.

[117] A. Bankar, B. Joshi, A. R. Kumar, and S. Zinjarde, "Banana peel extract mediated novel route for the synthesis of palladium nanoparticles," *Materials Letters*, vol. 64, no. 18, pp. 1951–1953, 2010.

[118] K. Mishra, N. Basavegowda, and Y. R. Lee, "Biosynthesis of Fe, Pd, and Fe-Pd bimetallic nanoparticles and their application as recyclable catalysts for $[3+2]$ cycloaddition reaction: a comparative approach," *Catalysis Science & Technology*, vol. 5, no. 5, pp. 2612–2621, 2015.

[119] M. Sathishkumar, K. Sneha, I. S. Kwak, J. Mao, S. J. Tripathy, and Y. S. Yun, "Phyto-crystallization of palladium through reduction process using *Cinnamom zeylanicum* bark extract," *Journal of Hazardous Materials*, vol. 171, no. 1–3, pp. 400–404, 2009.

[120] S. Momeni and I. Nabipour, "A simple green synthesis of palladium nanoparticles with sargassum alga and their electrocatalytic activities towards hydrogen peroxide," *Applied Biochemistry and Biotechnology*, vol. 176, no. 7, pp. 1937–1949, 2015.

[121] M. Khan, M. Khan, M. Kuniyil et al., "Biogenic synthesis of palladium nanoparticles using *Pulicaria glutinosa* extract and their catalytic activity towards the Suzuki coupling reaction," *Dalton Transactions*, vol. 43, no. 24, pp. 9026–9031, 2014.

[122] N. Edayadulla, N. Basavegowda, and Y. R. Lee, "Green synthesis and characterization of palladium nanoparticles and their catalytic performance for the efficient synthesis of biologically interesting di (indolyl) indolin-2-ones," *Journal of Industrial and Engineering Chemistry*, vol. 21, pp. 1365–1372, 2015.

[123] S. Lebaschi, M. Hekmati, and H. Veisi, "Green synthesis of palladium nanoparticles mediated by black tea leaves (*Camellia sinensis*) extract: catalytic activity in the reduction of 4-nitrophenol and Suzuki-Miyaura coupling reaction under ligand-free conditions," *Journal of Colloid and Interface Science*, vol. 485, pp. 223–231, 2017.

[124] M. Nasrollahzadeh, S. M. Sajadi, E. Honarmand, and M. Maham, "Preparation of palladium nanoparticles using

Euphorbia thymifolia L. leaf extract and evaluation of catalytic activity in the ligand-free Stille and Hiyama cross-coupling reactions in water," *New Journal of Chemistry*, vol. 39, no. 6, pp. 4745–4752, 2015.

[125] M. Nasrollahzadeh and S. Mohammad Sajadi, "Pd nanoparticles synthesized in situ with the use of *Euphorbia granulate* leaf extract: catalytic properties of the resulting particles," *Journal of Colloid and Interface Science*, vol. 462, pp. 243–251, 2016.

[126] B. Khodadadi, M. Bordbar, and M. Nasrollahzadeh, "Green synthesis of Pd nanoparticles at apricot kernel shell substrate using *Salvia hydrangea* extract: catalytic activity for reduction of organic dyes," *Journal of Colloid and Interface Science*, vol. 490, pp. 1–10, 2017.

[127] G. Lin, X. Yan, L. Pang et al., "Green synthesis of iron nanoparticles using Hizikia fusiformis extracts and study on properties of chromium remova," *Journal of Ocean University of China*, vol. 48, no. 8, pp. 118–124, 2018.

[128] E. Ituen, A. Singh, and L. Yuanhua, "Inhibitive effect of onion mesocarp extract-nickel nanoparticles composite on simultaneous hydrogen production and pipework corrosion in 1 M HCl," *International Journal of Hydrogen Energy*, vol. 45, no. 18, pp. 10814–10825, 2020.

[129] G. Elango, S. M. Roopan, K. I. Dhamodaran, K. Elumalai, N. A. Al-Dhabi, and M. V. Arasu, "Spectroscopic investigation of biosynthesized nickel nanoparticles and its larvicidal, pesticidal activities," *Journal of Photochemistry and Photobiology B: Biology*, vol. 162, pp. 162–167, 2016.

[130] Z. Vaseghi, A. Nematollahzadeh, and O. Tavakoli, "Plant-mediated Cu/Cr/Ni nanoparticle formation strategy for simultaneously separation of the mixed ions from aqueous solution," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 96, pp. 148–159, 2019.

[131] F. Lu, D. Sun, J. Huang et al., "Plant-mediated synthesis of Ag-Pd alloy nanoparticles and their application as catalyst toward selective hydrogenation," *ACS Sustainable Chemistry & Engineering*, vol. 2, no. 5, pp. 1212–1218, 2014.

[132] F. Luo, D. Yang, Z. Chen, M. Megharaj, and R. Naidu, "Characterization of bimetallic Fe/Pd nanoparticles by grape leaf aqueous extract and identification of active biomolecules involved in the synthesis," *The Science of the Total Environment*, vol. 562, pp. 526–532, 2016.

[133] A. Naseer, A. Ali, S. Ali 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*, vol. 9, no. 4, pp. 9093–9107, 2020.

[134] M. Nasrollahzadeh, F. Ghorbannezhad, Z. Issaabadi, and S. M. Sajadi, "Recent developments in the biosynthesis of Cu-based recyclable nanocatalysts using plant extracts and their application in the chemical reactions," *The Chemical Record*, vol. 19, no. 2-3, pp. 601–643, 2019.

[135] Z. Yu, C. Hu, L. Guan, W. Zhang, and J. Gu, "Green synthesis of cellulose nanofibrils decorated with Ag nanoparticles and their application in colorimetric detection of L-cysteine," *ACS Sustainable Chemistry & Engineering*, vol. 8, no. 33, pp. 12713–12721, 2020.

[136] Jigyasa and J. K. Rajput, "Bio-polyphenols promoted green synthesis of silver nanoparticles for facile and ultra-sensitive colorimetric detection of melamine in milk," *Biosensors and Bioelectronics*, vol. 120, pp. 153–159, 2018.

[137] H. Veisi, M. Kavian, M. Hekmati, and S. Hemmati, "Biosynthesis of the silver nanoparticles on the graphene oxide's surface using *Pistacia atlantica* leaves extract and its antibacterial activity against some human pathogens," *Polyhedron*, vol. 161, pp. 338–345, 2019.

[138] M. Nasrollahzadeh, M. Sajjadi, and S. M. Sajadi, "Green synthesis of Cu/zirconium silicate nanocomposite by using *Rubia tinctorum* leaf extract and its application in the preparation of *N*-benzyl-*N*-arylcyanamides," *Applied Organometallic Chemistry*, vol. 33, no. 2, pp. 4705–4717, 2019.