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Review

Plant-Based Extracts as Reducing, Capping, and Stabilizing Agents for the Green Synthesis of Inorganic Nanoparticles

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Abstract: The synthesis of inorganic nanoparticles for diverse applications is an active research area that involves physical and chemical methods, which typically are expensive, involve hazardous chemical reagents, use complex equipment and synthesis conditions, and consume large amounts of time and energy. Thus, green synthesis methods have emerged as eco-friendly and easy alternatives for inorganic nanoparticle synthesis, particularly the use of plant-based extracts from fruit juice, leaves, seeds, peel, stem, barks, and roots, which act as reducing, capping, and stabilizing agents, contributing to the Sustainable Development Goals and circular economy principles. Therefore, diverse inorganic nanoparticles have been synthesized using plant-based extracts, including gold, silver, titanium dioxide, zinc, copper, platinum, zirconium, iron, selenium, magnesium, nickel, sulfur, cobalt, palladium, and indium nanoparticles, which exhibit different biological activities such as antioxidant, antimicrobial, dye degradation, cytotoxic, analgesic, sedative, wound-healing, skin protection, sensor development, and plant-growth-promoting effects. Therefore, this review summarizes the advantages and limitations of plant-based extracts as reducing, capping, and stabilizing agents for inorganic nanoparticle green synthesis.

Keywords: nanotechnology; plants; food waste; circular economy; nanoscale materials; natural extracts; green synthesis; biological applications

1. Introduction

In the current scientific era, nanotechnology has emerged as an active research area with a wide range of applications, including physics, biology, chemistry, medicine, electronics, engineering, and environmental sciences [1], attributed to the superior physical, chemical, thermal, mechanical, and biological properties (surface area, stability, adsorption, optical, mechanical strength, lower, melting points, catalytic, antimicrobial, antioxidant, and biocompatibility) that nanomaterials exhibit in comparison with their bulk materials [2,3]. Various physical and chemical methods have been exploited to synthesize inorganic nanoparticles; however, these methods are expensive, involve hazardous chemical reagents, use complex equipment and synthesis conditions, and require huge energy and time consumption [4]. To overcome these drawbacks, green synthesis methods are a viable, technological, and eco-friendly alternative for the synthesis of NPs [4,5].

In the green synthesis approach, biological resources such as bacteria, fungi, yeast, viruses, algae, and plants have been investigated as reducing agents for synthesizing inorganic nanoparticles [4,5]. Particularly, the extract of different plant parts can be used, such as the aerial parts, flowers, leaves, roots, stem bark, and seeds, which contain bioactive compounds able to act as reducing agents during the synthesis of inorganic nanoparticles [2]. The main components typically required to reduce the oxidation state of a metal (often in a salt form) are polyphenols, flavonoids, and stilbenes, among others [4]. These compounds act as antioxidants; thus, they can interact with metallic salts to reduce the oxidation value of the metal [5]. In green synthesis using plant extracts, the concentration of these compounds varies depending on the method of extraction applied and the part of the plant used [4,6].

Regarding the plant-based sources of bioactive compounds, it has been reported that approximately 40–50% of global food waste globally comes from plant-based sources, including fruits, vegetables, roots, tubers, edible flowers, leaves, peel, and seeds. These sources can be used to obtain natural antioxidant compounds for synthesizing inorganic nanoparticles. This strategy of using plant-based extracts to synthesize inorganic nanoparticles directly contributes to the United Nations' Sustainable Development Goals for the 2030 Agenda and aligns with the principles of the circular economy, which focuses on recycling, recovery, and reutilization [7,8]. Therefore, this review aims to summarize the advantages and limitations of using plant-based extracts as reducing, capping, and stabilizing agents for the green synthesis of inorganic nanoparticles.

2. Synthesis of Inorganic Nanoparticles

The general methods for producing nanomaterials can be divided into physical and chemical approaches [9]. In physical methods, experimental conditions are controlled to create nanomaterials from bulk material or desired components. These methods start from bulk materials and are called "top-down" approaches. They encompass techniques like high-energy ball milling, inert gas condensation, laser ablation, wire explosion, arc discharge, and ion sputtering [10,11].

In chemical methods, nanomaterials are manufactured from atoms produced from ions in solution, which assemble to form the nanomaterials [11]. Since the synthesis begins with atoms, these methods are known as "bottom-up" approaches. Methods belonging to this category include chemical reduction, photochemical synthesis, sonochemical routes, electrochemical, solvothermal, micelles and nanoemulsions, interfacial synthesis, biological methods, thermolysis strategies (e.g., pyrolysis, spray pyrolysis), precipitation (mainly for semiconductors and oxides), solvated metal atom dispersion, and hybrid methods that systematically combine several of the previously mentioned methods to create intricate structures [12–14].

Due to the nature of the physical and chemical processes, their main disadvantages include high energy and solvent consumption to synthesize nanomaterials, which can increase costs and harm environmental and human health [12]. In this context, the green synthesis of nanoparticles has emerged as an active research area to reduce the negative impact of nanoparticles synthesized by chemical and physical methods.

3. Green Synthesis of Inorganic Nanoparticles

In the green synthesis methods for producing inorganic nanoparticles, bacteria, fungi, algae, and plants are used to reduce the oxidized state of metals, favoring the formation of nanoparticles. Plant-mediated nanoparticle (NP) synthesis can be performed by extracellular and intracellular methods. The extracellular methods involve using plant extracts or isolated phytochemicals as raw materials for the synthesis of NPs, while in the intracellular methods, the NP synthesis takes place inside the cells of plant tissues [2]. The most preferred route for the green synthesis of NPs is the use of plant extracts because this process typically requires ambient pressure and temperature, as well as neutral pH values, usually completed within a few minutes [5]. For the process, plant-extract-mediated bio-reduction involves mixing an aqueous extract with an aqueous solution of the relevant metal salts [14] (Figure 1).

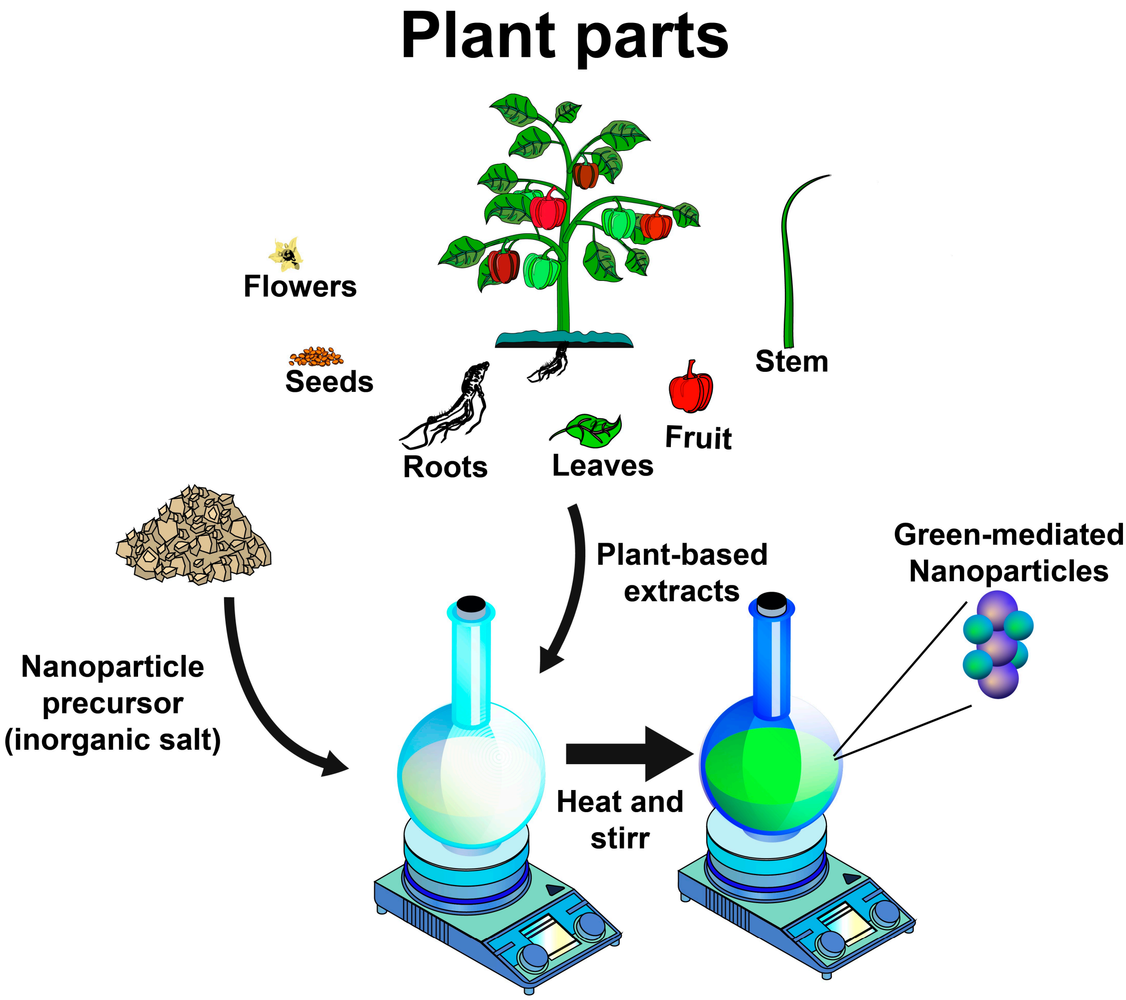

Figure 1. Schematic representation of typical green synthesis of inorganic nanoparticles using plant-based extracts.

Plants are excellent sources of biomolecules such as phytochemicals (polyphenols, flavonoids, terpenoids, alkaloids, and saponins), polysaccharides, and proteins, which act as reducing, capping, and stabilizing agents for the green synthesis of NPs [3,5]. The roots, seeds, flowers, leaves, peels, fruits, and stem barks of various plant species have been investigated as potential sources for synthesizing NPs [3]. Nonetheless, the source of a plant extract and type and the concentration of phytochemicals, as well as its extraction method, are known to influence the characteristics of a nanostructure due to their hydroxyl and ketone groups, which are capable of binding to metals and showing chelation [4].

4. Inorganic Nanoparticles Synthesized Using Plant-Based Extracts

As discussed in the preceding sections, using plant-based extracts as reducing and stabilizing agents for synthesizing inorganic nanoparticles is an opportunity for developing greener synthesis approaches. Therefore, diverse inorganic nanoparticles have been synthesized using plant-based extracts, including gold, silver, titanium dioxide, zinc, copper, platinum, zirconium, iron, selenium, magnesium, nickel, sulfur, cobalt, palladium, and indium nanoparticles, which exhibit different biological activities for diverse applications (Figure 2), as described below.

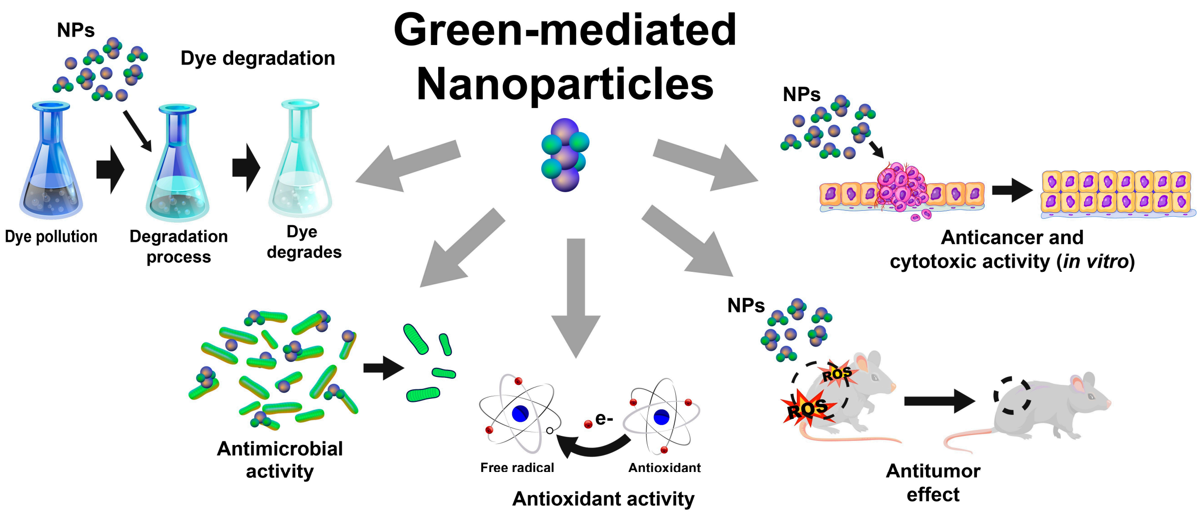

Figure 2. Schematic representation of most-reported applications of green-mediated inorganic nanoparticles.

4.1. Gold Nanoparticles

Gold nanoparticles (AuNPs) have proved to be a versatile material for diverse applications [15–18]. Therefore, many routes for its synthesis have been developed involving the reduction of gold cations (Au^{1+} or Au^{3+}) to gold-zerovalent (Au^0) [15,19,20], highlighting the green synthesis route, where diverse rich bioactive compounds from plant-based extracts reduce gold precursors. Then, Au^+ ions are bound and capped by phytochemicals to form stable AuNPs [19,21,22] (Table 1). In most cases, the reduction of gold is monitored by a color change from pale pink to ruby red, or to dark violet from yellow for $AuCl_3$ and $HAuCl_4$, respectively, as AuNPs precursors [16,20,21]. The green-mediated AuNPs exhibit XRD patterns of a face center cubic structure [(111), (200), (220), and (311)] [16,18] and UV–visible absorption peaks between 530 and 550 nm [23], with an Eg value of 1.9 eV [20].

Table 1. Gold nanoparticles synthesized by green chemistry using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Au salt	*Ricinus communis*	Seed	Methanolic	Spherical	<100	Antimicrobial	[15]
$AuCl_3$	*Vitis vinifera*	Fruit	Aqueous	NI	NI	Antimicrobial	[18]
$HAuCl_4$	*Moringa oleifera*	Leaf	Methanolic	Spherical	4	Antimicrobial, antioxidant, cytotoxic, dye degradation	[19]
$AuCl_3$	*Jatropha integerrima*	Flower	Aqueous	Spherical	37	Antimicrobial	[20]
$HAuCl_4$	Licorice	Root	Aqueous	Spherical	53	Antimicrobial, anticancer	[21]
$HAuCl_4$	*Pistacia chinensis*	Seed	Aqueous	Spherical	10–100	Analgesic, sedative	[23]
$HAuCl_4$	*Zingiber officinale*	Root	Aqueous	Spherical	5–53	Antimicrobial, antioxidant, cytotoxic	[24]
$HAuCl_4$	*Clerodendrum inerme*	Leaf	Aqueous	Spherical	5.8	Antimicrobial, antioxidant, cytotoxic	[25]

NI: no information.

In general, the methanolic and aqueous extracts from flowers, roots, seeds, fruits, and leaves of different plants have been used for the green synthesis of AuNPs with spherical shapes and sizes from 4 to 100 nm for diverse applications [15,18,20,23]. Khan et al. [25]

reported that AuNPs (5.8 nm) can be synthesized using *Clerodendrum inerme* aqueous leaf extract, which exhibited antimicrobial, antioxidant, and cytotoxic activities. Similar trends were reported in AuNPs (53 nm) synthesized using licorice root extract, which exhibited antioxidant, antimicrobial, and anticancer activities in a concentration-dependent manner. These activities are associated with the bioactive compounds of the licorice root extract that includes phenolics, glycosides, organic acids, terpenes, and fatty acids [21]. Furthermore, it has been reported that the green synthesis of AuNPs is influenced by the concentration of gold precursor [20,21].

Boruah et al. [19] used *Moringa oleifera* methanolic leaf extract to synthesize spherical-shaped AuNPs with size of 4 nm. They exhibited diverse biological properties, such as antimicrobial, antioxidant, and cytotoxic activities in red blood cells; moreover, they also showed photocatalytic properties against methylene blue dye. The authors suggested that the bioactive compounds of the extract contributed to the enhanced biological and technological properties of the AuNPs. Other studies have found similar trends when using green-mediated AuNPs from *Zingiber officinale* root (antimicrobial, antioxidant, and cytotoxic properties) [24], *Ricinus communis* seeds [15], *Jatropha integerrima* flower [20], and *Vitis vinifera* fruit (antimicrobial activity) [18]. It was also reported that AuNP-mediated *Pistacia chinensis* exhibited analgesic and sedative properties in an acetic-acid-induced writhing model in a dose-dependent manner [23]. Furthermore, extracts from plants such as *Phoenix dactylifera* [18], *Simarouba glauca* [22], *Salvia officinalis*, *Lippia citriodora*, *Pelargonium graveolens*, *Punica granatum* [17], and *Centella asiatica* [16] have been investigated as reducing, capping, and stabilizing agents for the green synthesis of AuNPs.

4.2. Silver Nanoparticles

Among the metal-based nanoparticles, silver nanoparticles (AgNPs) have become very popular in the research community due to their wide range of applications, including for antimicrobial, antioxidant, anticancer, and photocatalytic dye degradation applications [26–29]. In this context, the green synthesis of AgNPs using plant-based extracts as reducing agents (Ag^+ to Ag^0) has gained significant attention in recent years [30–32], with silver nitrate ($AgNO_3$) being the most used precursor for their synthesis [29,31–33]. After mixing $AgNO_3$ aqueous solution and plant extracts, the color of the reaction medium changes from yellowish green to brownish [34,35], suggesting the conversion of Ag ions (Ag^+) to metallic silver (Ag^0) [31]. The green-mediated AgNPs exhibited surface plasmon resonance around 400–450 nm [31] with a crystalline nature and a face-centered cubic structure XRD pattern of (111), (200), (220), and (331) [35]. On the other hand, some green-synthesized AgNPs exhibited good stability (zeta potential of −15.8 to 3.31 mV) [32]. Various plant-based extracts have been investigated to prepare spherical AgNPs with sizes < 100 nm (Table 2).

Table 2. Green synthesis of silver nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
$AgNO_3$	*Achillea millefolium*	Plant	Methanolic	Spherical	18	Antimicrobial, antioxidant	[28]
$AgNO_3$	*Annona muricata*	Peel	Aqueous	Spherical	<100	Anticancer	[30]
$AgNO_3$	*Zataria multiflora*	Leaf	Aqueous	Rod-shape	25	Antimicrobial	[31]
$AgNO_3$	*Teucrium polium*	Leaf	Aqueous	Spherical	70–100	Antitumor	[33]
$AgNO_3$	*Brillantaisia patula*, *Crossopteryx febrifuga*, *Senna siamea*	Leaf	Aqueous	Spherical	45–110	Antimicrobial	[35]
$AgNO_3$	*Gymnema sylvestre*	Leaf	Aqueous	Spherical	20–30	Antimicrobial	[36]
$AgNO_3$	*Lysiloma acapulcensis*	Stem, roots	Aqueous	Spherical	5	Antimicrobial	[37]
$AgNO_3$	Onion, tomato	Fruit	Ethanolic	Spherical	5–100	Dye degradation	[38]

Various plants such as *Zataria multiflora*, *Brillantaisia patula*, *Crossopteryx febrifuga*, *Senna siamea*, *Gymnema sylvestre*, *Lysiloma acapulcensis*, and *Achillea millefolium* have been used to synthesize silver AgNPs, using extracts from different parts of the plant, such as the leaves, stems, and roots [29,31,33,34]. It was reported that factors such as the plant extract, pH, and temperature significantly influenced the green synthesis of AgNPs [39]. These green-mediated AgNPs have exhibited antimicrobial properties against various pathogenic bacteria and fungi [27,28,31,35–37]. According to the authors, the antimicrobial activity of AgNPs is related to their ability to cause cell breakdown, which promotes changes in the cell membrane's permeability.

It has been found that green-synthesized AgNPs prepared from aqueous extracts derived from *Annona muricata* peel, *Teucrium polium* leaves, and *Cynara scolymus* leaf extracts exhibit anticancer properties at very low concentrations, attributed to their apoptotic properties [30,34,38–40]. Additionally, green-synthesized AgNPs using *Achillea millefolium* and *Annona muricata* extracts exert anti-inflammatory and antioxidant activities [28,30]. Chand et al. [38] reported that AgNPs synthesized using onion and tomato extracts exhibited photocatalytic properties against cationic dyes in aqueous solutions, with the effect attributed to the capability of AgNPs to produce reactive oxygen species under the UV region [38].

In general, the plant-based extracts used for AgNPs green synthesis proceed through reducing silver ions, primarily by the capability to donate electrons. Tannins were found to play a key role in reducing and capping AgNPs in most cases [39]. Furthermore, some plant-based extracts, such as *Centella Asiatica* and Tridax, were used to synthesize silver oxide (Ag_2O) nanoparticles, which exhibited photocatalytic properties against acid orange dye [27].

4.3. Titanium Dioxide Nanoparticles

Titanium dioxide nanoparticles (TiO_2NPs) are one of the most investigated materials due to their photocatalytic properties and chemical and thermal stability in diverse industrial uses [41]. They have been typically synthesized by chemical routes [42]; however, TiO_2NPs have been synthesized using green approaches using different plant-based extracts and titanium-isopropoxide or titanium dioxide solution as chemical precursors (Table 3). In most cases, a light-green formation after mixing TiO_2 precursor and plant extracts indicates the reduction of Ti ions [43]. The green-mediated TiO_2NPs exhibited a strong UV absorption peak around 380 to 400 nm and a crystalline structure in their anatase and rutile forms [Miller index = (101), (110), (103), (004), (112), (200), (105), and (211)] [41] with negative zeta potential (−18.7 to −11.5 mV) and large surface area (105 m^2g^{-1}) [44–46].

Table 3. Green synthesis of titanium dioxide nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Titanium dioxide solution (5 mM)	*Azadirachta indica*	Leaf	Aqueous	Spherical	15–50	Antibacterial	[41]
Titanium dioxide solution (5 mM)	*Sesbania grandiflor*	Leaf	Aqueous	Square and spherical	43–56	NI	[43]
Titanium dioxide solution (5 mM)	*Ocimum sanctum*	Leaf	Aqueous	Spherical, polygonal, and square	75–123	Wound-healing properties	[44]
Titanium tetra isopropoxide	*Mentha arvensis*	Leaf	Ethanolic	Spherical	20–70	Antimicrobial	[45]
Titanium-isopropoxide (5 mM)	*Syzygium cumini*	Leaf	Aqueous	Spherical	18	Wastewater treatment	[46]

Thakur et al. [41] synthesized TiO_2NPs using *Azadirachta indica* aqueous leaf extract as a stabilizing and reducing agent, with anatase and rutile structures, spherical shapes, and sizes from 15 to 50 nm, which exhibited antibacterial activity against different Gram-negative bacteria. Similarly, TiO_2NPs (spherical and 20–70 nm in size) prepared by green synthesis using *Mentha arvensis* leaf extracts showed antimicrobial activity in a dose-dependent manner [45]. According to the authors, the phytochemicals such as alkaloids, terpenoids, and phenolics in *Azadirachta indica* and *Mentha arvensis* acted as stabilizing and reducing agents during TiO_2 synthesis. The antimicrobial effect of TiO_2 is due to its capability to interact with the cell wall of microorganisms, promoting cell death [41,45].

Sethy et al. [46] reported that TiO_2NPs (anatase phase) synthesized using an aqueous leaf extract of *Syzygium cumini* exhibited photocatalytic properties for removing Pb from wastewater, associated with its ability to generate OH radicals in the presence of light. On the other hand, recent research also showed that TiO_2NPs (anatase form, spherical and polygonal shape, 130 nm in size), prepared by a green synthesis approach using *Ocimum sanctum* leaf extract, could improve the wound-healing efficacy of chitosan hydrogels in diabetics rats [44]. This effect was attributed to the antimicrobial properties of TiO_2 [45]. The authors suggested that the presence of phytochemicals in plant-based materials plays an important role in the reduction, capping, and stabilization of TiO_2 [44,46].

Srinivasan et al. [43] synthesized TiO_2NPs in the anatase phase using aqueous leaf extracts of *Sesbania grandiflora*, which exhibited square and spherical shapes with sizes ranging from 43 to 56 nm, completing the reduction at room temperature. Furthermore, the study revealed that TiO_2NPs exhibited toxicological effects against zebrafish embryos in a dose-dependent manner. Therefore, further studies are needed to fully evaluate the possible toxic effects of TiO_2NPs synthesized by green synthesis methods.

Additionally, the green synthesis of TiO_2NPs has been performed using different plant-based extracts, including *Moringa oleifera* [47], *Psidium guajava* [48], *Arbor tristis* [49], *Eclipta prostrata* [50], and *Ageratina altissima* leaves [51], *Vigna unguiculata* seeds [52], *Calotropis gigantea* flowers [53], *Aloe vera* [54], *Vigna radiata* legumes [55], and *Curcuma longa* plant [56]. These TiO_2NPs exhibited potential industrial, environmental, and pharmaceutical applications due to their wound healing, antimicrobial, antioxidant, dye photocatalytic degradation, acaricidal, and cytotoxic properties [47,49,51–53,55].

4.4. Zinc Nanoparticles

Zinc nanoparticles (ZnNPs) have unique features like being nontoxic, low-cost, biocompatible, multifunctional, and eco-friendly. They have been investigated for diverse applications due to their antimicrobial, antifungal, nanomedicine, antioxidant, and photocatalytic activities [57–59]. ZnNPs have been green-synthesized using extracts from the leaves, flowers, stem bark, and fruit juice from various plant species (Table 4), which are mostly spherical, with sizes smaller than 60 nm. The most common Zn precursors are zinc nitrate and zinc acetate [60,61]. After mixing the plant extracts and Zn precursors, a white or yellowish paste is observed, indicating successful formation [62,63]. The green-mediated ZnNPs exhibited a strong UV absorption peak around 300–400 nm [63,64] and a crystalline structure in their hexagonal wurtzite phase [Miller index = (100), (002), (101), (102), (110), (200), (112), (201), (004), and (202)], where each Zn^{+2} ion was ordered in a tetragonal coordination with a polar symmetry throughout the hexagonal axis [62,65]. These ZnNPs exhibited Eg values from 2.67 to 3.37 eV and a negative zeta potential (−40 mV) [63,65].

Table 4. Green synthesis of zinc dioxide nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Zinc nitrate	*Limonia acidissima*	Fruit (juice)	Aqueous	Spherical	27	Antimicrobial, dye degradation	[60]
Zinc nitrate hexahydrate	*Xanthium indicum*	Leaf	Ethanolic	Spherical	50–60	Antioxidant, antimicrobial, antifungal, cytotoxicity, and photocatalyticactivities.	[66]
Zinc acetate dihydrate	*Eriobutria japonica*	Seed	Aqueous	Spherical	<50	Antimicrobial, antioxidant, Dye degradation	[57]
Zinc nitrate	*Hibiscus sabdariffa*	Flower	Aqueous	Spherical	8–30	Dye degradation	[58]
Zinc nitrate	*Euphorbia hirta*	Leaf	Ethanolic	Spherical	20–25	Antimicrobial, antifungal	[59]
Zinc nitrate hexahydrate	*Hydnocarpus alpina*	Leaf and stem bark	Ethanolic	Spherical	38.84	Antimicrobial	[67]
Zinc nitrate hexahydrate	*Cayratia pedata*	Leaf	Aqueous	Horizontal shape	52.24	Enzymeimmobilization	[68]
Zinc acetate dihydrate	*Lippiaadoensis*	Leaf	Aqueous	Spherical and nanorod	19.78	Antimicrobial	[61]

Madhukara et al. [60] used *Limonia acidissima* juice for zinc ferrite ($ZnFe_2O_4$) nanoparticle synthesis with photocatalytic properties against Evans blue and methylene blue dyes under visible light in a concentration-dependent manner, as well as antibacterial activity against in a strain- and dose-dependent manner. It has been reported that green-synthesized ZnNPs using *Eriobutria japonica* seed [57], *Hibiscus sabdariffa* [58], or *Hydnocarpus alpina* [67] extracts are active against methylene blue dye in a dose-dependent manner; moreover, they exhibit antimicrobial activity against various bacterial strains [57,67]. However, ZnNPs exhibit higher antimicrobial activity against Gam-negative bacteria than Gram-positive bacteria due to differences in the thickness of the peptidoglycan layer; thus, ZnNPs can enter cells and inhibit their replication and growth. Additionally, ZnNPs synthesized using *Lippia adoensis* [61], as well as *Euphorbia hirta* extracts, showed antibacterial activity in a strain- and dose-dependent manner.

Bitopan et al. [66] studied the biocompatibility of ZnNPs using *Xanthium indicum* leaf extract as a reducing and stabilizing agent and reported that the ZnNPs did not show hemolytic action at lower concentrations; however, negative effects were observed at higher concentrations (>25 mg/mL). The authors mentioned that the ZnNPs synthesized by the green route demonstrated the weakest cytotoxic effects compared with those obtained by the chemical route. Additionally, Ashwini et al. [68] synthesized ZnNPs using *Cayratia pedate* as an enzyme glucose oxidase immobilizer for biomedical applications.

4.5. Copper Nanoparticles

Copper nanoparticles (CuNPs) are gaining significant attention due to their electrical, optical, mechanical, catalytic, and antimicrobial properties [69]. They have been green-synthesized using aqueous extracts from the leaves, flowers, and fruits from various plants for environmental and antimicrobial purposes [3,70–72]. The most common precursors for CuNPs are copper (II) sulfate pentahydrate [3,69,71,73], cupric nitrate trihydrate [70], copper chloride (II) [71,73,74], and copper (II) acetate [75] (Table 5). The formation of CuNPs is confirmed through a color change of the reaction mixture from yellowish to brownish [71,73], yellow to green [3], or blue to brown [72], depending on the Cu precursor.

Green-mediated CuNPs exhibited a UV absorption peak ranging from 269 to 580 nm, which depends on the CuNPs' energy state [3,69]. In most cases, CuNPs exhibited a monocyclic configuration [Miller index = (110), (111), (220), (800), and (713)] [71]. These CuNPs are mostly spherical with sizes ranging from 2 to 80 nm [3,70–74] and a negative zeta potential (−33.98 mV) [74].

Table 5. Green synthesis of copper nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Copper (II) Sulfate pentahydrate	*Celastrus paniculatus* Willd	Leaf	Aqueous	Spherical	2–10	Dye degradation, antifungal	[3]
Cupric nitrate trihydrate	*Genus santalum*	Leaf	Aqueous	Irregular	22	Dye degradation	[70]
Copper (II) sulfate pentahydrate	*Calotropis procera*	Leaf	Aqueous	Spherical	20–80	Antimicrobial	[73]
Copper chloride (II)	*Tinospora cardifolia*	Leaf	Aqueous	Spherical	63	Antimicrobial	[74]
Copper sulfate pentahydrate	*Duranta erecta*	Fruit	Aqueous	Spherical	70	Dye degradation	[69]
Copper (II) acetate	*Lantana camara*	Flower	Aqueous	Rod-shape	15–23	Dye degradation	[75]
Copper chloride	*Jatropha curcas*	Leaf	Aqueous	Spherical	10–12	Dye degradation	[71]
Copper sulphate	*Cissus vitiginea*	Leaf	Aqueous	Spherical	5–20	Antimicrobial	[72]

Mali et al. [3] used *Celastrus paniculatus* aqueous leaf extract as a reducing agent to synthesize spherical CuNPs (Cu purity of 79.87%, size of 2–10 nm) with photocatalytic and antifungal properties. Similarly, it was reported that CuNPs (spherical and size of 63 nm) prepared using *Tinospora cardifolia* aqueous leaf extract exhibited antibacterial activity and could be impregnated in cotton fabrics [74]. Additionally, *Cissus vitiginea* leaf extract was used to synthesize CuNPs (spherical and size of 5–20 nm) active against urinary infection pathogens [72]. The antimicrobial properties of CuNPs are based on changes in the cell structure of microorganisms, leading to cell death [3,72,74]. In general, the biomolecules present in plant extracts act as reducing and stabilizing agents during the formation of CuNPs. Particularly, flavonoids are transformed from the enol form to the keto form by releasing a reactive hydrogen atom that reduces Cu^{2+}, which is facilitated at pH 7 [3].

Ismail et al. [69] reported that zerovalent CuNPs synthesized using *Duranta erecta* aqueous fruit extract showed photocatalytic activity against anionic dyes in a dose-dependent manner. Similarly, CuNPs with photocatalytic properties against anionic and cationic dyes could be synthesized using *Jatropha curcas* leaf extract [71].

Additionally, Chowdhury et al. [75] synthesized copper oxide nanoparticles (CuONPs) with *Lantana camara* flower extract in an alkaline hydrolysis process. The resulting rod-shaped nanoparticles (15–23 nm in size) exhibited catalytic properties against acrylonitrile and aniline. Similarly, CuONPs synthesized using *Calotropis procera* leaf extract exhibited antimicrobial activity. Furthermore, Cu-based nanoparticles have also been doped with inorganic materials to enhance their physicochemical properties. Green-synthesized Cu-doped MoO_3 (Cu-MoO_3) nanoparticles prepared using *Genus Santalum* aqueous leaf extract enhanced the photocatalytic properties in degrading hazardous organic pollutants [70]. Cu-doped silver (Cu-Ag) nanoparticles could remove dyes from aqueous solutions [76], while copper–nickel hybrid nanoparticles synthesized using extracts from *Zingiber officinale* rhizomes showed photocatalytic activity against crystal violet dye [77].

4.6. Platinum Nanoparticles

Over the past few years, researchers have been exploring the use of aqueous extracts from various plant materials, including *Cordyceps militaris*, *Nymphaea tetragona*, *Atriplex halimus*, olive, Saudi's dates, and tea polyphenols, along with their parts, to synthesis platinum nanoparticles (PtNPs) (Table 6). For this purpose, hexachloroplatinic acid (H_2PtCl_6) is commonly used as precursor to produce spherical-shaped PtNPs ranging from 1 to 13 nm [78–80]. After mixing plant extracts and H_2PtCl_6, the color of the reaction mixture gradually changed from pale yellow to brown or black, indicating the reduction to Pt^0 [79–83]. The green-mediated PtNPs exhibited surface plasmon resonance around 230 to 295 nm and a cubic structure XRD pattern of (111), (200), (220), and (311) [81,82] with a zeta potential of −17.28 to −0.0536 mV [80,84,85].

Table 6. Green synthesis of platinum nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
H_2PtCl_6	*Cordyceps militaris*	Flower	Aqueous	Spherical	13	Antimicrobial, antioxidant	[80]
H_2PtCl_6	Olive	Leaf	Aqueous	Spherical	9.2	Inhibitory effect of aspartate aminotransferase	[83]
H_2PtCl_6	*Nymphaea tetragona*	Flower	Aqueous	Spherical	4	Antioxidant, skin protection	[81]
H_2PtCl_6	*Atriplex halimus*	Leaf	Aqueous	Spherical	3	Antimicrobial, antioxidant	[82]
H_2PtCl_6	Ajwa and Barni dates	Fruit	Aqueous	Spherical	1–2	Antimicrobial, anticancer agent	[79]
H_2PtCl_6	Tea polyphenols	Leaf	Aqueous	Spherical	2.7	H_2O_2 detection	[78]

PtNPs have shown promising antimicrobial activity against pathogenic bacteria [79,80,82], as well as antioxidant capacity [80–82]. Additionally, PtNPs have been found to possess anticancer properties [79] and inhibit serum aspartate aminotransferase in serum levels of patients with chronic liver disease [83]. PtNPs have also demonstrated antiaging effects/skin protection by promoting collagen I biosynthesis in HFF-1 cells and inhibiting tyrosinase activity in A375 cells [81]. On the other hand, PtNPs with polycrystalline structures were used to develop sensors for hydrogen peroxide detection [78]. All authors agreed that bioactive compounds in plant-based extracts exerted capping and reducing effects, both associated with metal reduction and contribute as a stabilizing agent to forming PtNPs, avoiding their agglomeration [78,79,82]. Furthermore, green synthesis of PtNPs has been performed using hyacinth plant extracts [85] and seaweed *Padina gymnospora* [82] with potential biomedical applications.

4.7. Zirconium Nanoparticles

Zirconium (ZrNPs) nanoparticles can be synthesized by green chemistry methods with high purity using plant-based extracts for diverse applications, such as antimicrobial and dye photocatalytic degradation [86]. They can be prepared from various precursors, including zirconium isopropoxide [87], zirconylchloride octahydrate [88], zirconyl nitrate [84], and zirconyl chloride [89]. After mixing a Zr precursor and plant extract, color changes from yellow to brown [89] or milky white formation indicates the formation of ZrNPs [88]. Green-mediated ZrNPs exhibited monocyclic structure of baddeleyite [XRD (111), (002), (022), (031), and (131)] [90], a UV absorption peak around 275 nm, an Eg value of 3.7 eV [91], and a zeta potential of −32.8 mV [88,92]. The ZrNPs had cubic, spherical, triangular, and oval shapes with sizes from 10 to <200 nm [87,88] (Table 7).

Table 7. Green synthesis of zirconium nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Zirconium isopropoxide	*Azadirachta indicia*	Gum of the bark	Aqueous	Irregular	<200	Antimicrobial	[87]
Zirconylchloride octahydrate	*Laurus nobilis*	Leaf	Aqueous	Cubic	20–100	Antimicrobial	[88]
Zirconyl nitrate	*Sphagneticola trilobata*	Leaf	Aqueous	Spherical, triangular, and oval	20–100	Antimicrobial	[86]
Zirconyl chloride	*Phyllanthus niruri*	Leaf	Aqueous	Spherical	121	Antimicrobial, dye degradation	[89]
Zirconylchloride octahydrate	*Sapindus mukorossias*	Pericarp	Aqueous	Spherical	10	Dye degradation	[93]
H_2PtCl_6	Tea polyphenols	Leaf	Aqueous	Spherical	2.7	H_2O_2 detection	[78]

Kazi et al. [86] used aqueous leaf extracts from *Sphagneticola trilobata* to synthesize ZrNPs of various shapes and sizes (20 to 100 nm). These nanomaterials showed antimicrobial properties and antimalarial activity. Similarly, spherical ZrNPs (121 nm) synthesized using *Phyllanthus niruri* aqueous leaf extracts, cubic ZrNPs obtained from *Laurus nobilis* (20 to 100 nm), and neem-gum nanoparticles displayed antimicrobial activity. In all cases, the antimicrobial effects of ZrNPs were dose-dependent. According to the authors, the antimicrobial properties of ZrNPs are related to their surface energy and surface-related interactions, leading to cell death by disrupting cell membranes and altering membrane fluidity [87–89].

Regarding environmental applications, ZrNPs synthesized by green methods with extracts from the pericarp of *Sapindus mukorossias* and leaves of *Phyllanthus niruri* exhibited photocatalytic properties for different dyes. These effects were attributed to the photocatalytic and adsorptive properties of ZrNPs [89,93].

The authors agreed that the presence of biomolecules in the plant-based extracts played a crucial role in reducing, capping, chelating, and stabilizing the conversion to ZrNPs due to their antioxidant properties [86,87,89,93]. These phytochemicals also helped to form and stabilize the octahedral complex of Zr^{2+} phytochemicals [94]. Moreover, zirconium oxide (ZrO_2) nanoparticles can be synthesized using different plant-based extracts, including *Euclea natalensis* roots [95], *Salvia Rosmarinus* leaves [96], *Helianthus annuus* seeds [91], *Nephelium lappaceum* fruit [90], and *Nyctanthes arbortristis* flowers [92] for diverse industrial applications.

4.8. Iron Nanoparticles

Iron oxide nanoparticles (Fe_2O_3NPs) have gained significant attention due to their unique physicochemical and catalytic properties for environmental and biomedical applications [97,98], mainly those synthesized by green routes using plant-based extracts. Fe_2O_3NPs can be prepared from various precursors, including ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) [97], ferric nitrate ($Fe(NO_3)_3 \cdot 9H_2O$) [99], and ferrous sulfate ($FeSO_4$) [100]. The formation of a black precipitate ensures the formation of α-Fe_2O_3 nanoparticles [101] or Fe_3O_4 [102], which are corroborated by the XRD patterns [101]. The nanoparticles exhibited spherical, semispherical, and cubic shapes with sizes ranging from 4 to 200 nm [97,100,103] (Table 8).

Table 8. Green synthesis of iron nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Ferric chloride hexahydrate	*Plantago major*	Leaf	Aqueous	Spherical	4–30	Dye degradation	[97]
Ferric nitrate	*Platanus orientalis*	Leaf	Aqueous	Spherical	38	Antimicrobial	[99]
$FeSO_4$	*Ixora finlaysonian*	Plant	Methanolic	Rectangular and Cubic	50–200	Antioxidant, Dye degradation	[100]
Ferric chloride hexahydrate	*Carica papaya*	Leaf	Aqueous	Irregular	21	Dye degradation, antimicrobial	[101]
Ferric chloride hexahydrate	*Ficus carica*	Fruit	Aqueous	Core-shell	9	NI	[104]
Ferric chloride hexahydrate	*Phoenix dactylifera*	Leaf	Aqueous	Spherical	22	Antioxidant	[102]
Ferric chloride hexahydrate	*Withania coagulans*	Fruit	Aqueous	Rods	16	Dye degradation	[105]
Ferric chloride hexahydrate	Pomegranate	Seed	Aqueous	Semi-spherical	25–55	Dye degradation	[103]
Ferric chloride hexahydrate	*Rhus punjabensis*	Plant	Aqueous	Spherical	41	Antimicrobial, antioxidant, anticancer	[98]

Generally, the most common form of green-synthesized iron nanoparticles is iron oxide (α-Fe_2O_3), which has been investigated for dye degradation, antimicrobial, and antioxidant purposes [103–105]. In this context, Lohrasbi et al. [97] used an aqueous extract of *Plantago major* leaves to prepare spherical Fe_2O_3NPs with sizes from 4 of 30 nm for environmental applications, while *Ficus carica* fruit extract was used in core–shell form with an average size of 9 nm. Additionally, Fe_2O_3 or Fe_3O_4 iron nanoparticles synthesized using *Phoenix dactylifera* aqueous leaf extract were found to exhibit antioxidant properties [102]. Nas et al. [98] reported that Fe_2O_3NPs synthesized using *Rhus punjabensis* extract can be used for antimicrobial, antioxidant, and anticancer applications. This effect is associated with the functional groups of the phenolics and flavonoids on the surface of the nanoparticles [98].

Devi et al. [99] reported that *Platanus orientalis* leaf extract can be used for the green synthesis of spherical Fe_2O_3NPs with an average size of 38 nm. These nanoparticles exhibited antifungal activity in a dose-dependent manner, attributed to the capability of Fe_2O_3NPs to disrupt microbial cell walls. Similarly, it was reported that Fe_2O_3NPs with irregular shapes and an average size of 21 nm can be synthesized using *Carica papaya* leaf extract, exhibiting moderate antimicrobial and photocatalytic properties in a dose-dependent manner [101]. During the green synthesis of Fe_2O_3NPs, the phytochemicals of plant extracts can reduce metallic salts to nanoparticles and act as stabilizing agents, preventing the aggregation of nanoparticles. The bioactive compounds reacted with the iron ions to give Fe_2O_3NPs, as the first-row transition metals are oxidation-prone. However, it is possible that the phytochemicals are not able to reduce Fe^{3+} to Fe^0 [99,101].

Furthermore, *Withania coagulans* extract was used as a reducing agent to prepare α-Fe_2O_3 nanorods (16 nm) with photocatalytic and antimicrobial activities [105]. Similarly, it was reported that using pomegranate seed extract, semispherical Fe_2O_3NPs (25–55 nm) exhibited the catalytic degradation of reactive blue dyes under UV light [103]. On the other hand, Fe-based nanoparticles doped with other inorganic materials showed enhanced physicochemical properties. Younas et al. [100] found that green-synthesized Fe–Cu bimetallic nanoparticles using *Ixora finlaysonian* leaf extract with rectangular and cubic shapes and sizes from 50 to 200 nm exhibited antioxidant and photocatalytic dye-degradation activities.

4.9. Selenium Nanoparticles

Selenium nanoparticles (SeNPs) are biocompatible compounds that exhibit low toxicity and high biological activities, which can be synthesized by green chemistry using plant-based extracts from fruits, leaves, peel, and plants such as *Crataegus monogyna* [106], *Melia azedarach* [107], *Rosmarinus officinali* [108], orange [109], *Cleistocalyx operculatus* [110], *Portulaca oleracea* [111], *Urtica dioica* [112], *Abelmoschus esculentus* [113], *Cordia myxa* [114], *and Withania somnífera* [115], with sodium selenite (Na_2SeO_3), selenium dioxide (SeO_2), and selenious acid (H_2SeO_3, as SeNPs precursors [106,110,115]. The formation of SeNPs can be identified by a color change from light green to brick red [107], colorless to light pink or red [106,114], or from pale yellow to deep red [106,109]. SeNPs exhibited a UV absorption peak ranging from 200 to 302 nm with monocyclic and trigonal phases [106–110] and a zeta potential of −64 mV [113]. These nanoparticles are spherical with sizes ranging from 2 to 200 nm [110,111] and exhibit antioxidant, antimicrobial, antiviral, anticancer, and photocatalytic activities [106,107,111,115] (Table 9).

Table 9. Green synthesis of selenium nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Sodium selenite	*Crataegus monogyna*	Fruit	Methanolic	Spherical	30–60	Anticancer antioxidant,	[106]
Sodium selenite	*Melia azedarach*	Leaf	Aqueous	Spherical	74	Antifungal	[107]
Sodium selenite	*Rosmarinus officinali*	Plant	Aqueous	Spherical	20–40	Antimicrobial	[108]
Sodium selenite	Orange	Peel	Aqueous	Spherical	16–95	Antimicrobial	[109]
Selenium dioxide	*Cleistocalyx operculatus*	Leaf	Ethanolic	Spherical	50–200	Antimicrobial	[110]
Sodium selenite	*Portulaca oleracea*	Leaf	Aqueous	Spherical	2–22	Antimicrobial, antiviral, mosquitocidal	[111]
Selenium dioxide	*Urtica dioica*	Leaf	Aqueous	Spherical	85–162	Antimicrobial, anticancer	[112]
Sodium selenite	*Abelmoschus esculentus*	Plant	Aqueous	Spherical	30	Antimicrobial	[113]
Sodium selenite	*Cordia myxa*	Fruit	Aqueous	Spherical	42–61	Anticancer	[114]
Selenious acid	*Withania somnifera*	Leaf	Ethanolic	Spherical	45–90	Antioxidant, antimicrobial, antiproliferative, dye degradation	[115]

Barzegarparay et al. [106] reported that green-synthesized SeNPs using *Crataegus monogyna* methanolic fruit extract exhibited anticancer activity; using an ethanolic leaf extract from *Withania somnifera* and *Cordia myxa* aqueous fruit extract, SeNPs showed antiproliferative properties [114,115]. This effect was attributed to the apoptotic properties of SeNPs, which were able to arrest the C2/M cell cycle [106], as well as to their antioxidant activity [106,115].

Additionally, SeNPs prepared using *Melia azedarach* aqueous leaf extract exhibited antifungal properties [107], while those synthesized using *Rosmarinus officinali*, *Abelmoschus esculentus*, *Cleistocalys operculants* leaves, and orange peel extracts exhibit antimicrobial activity [108–110,113]. *Portulaca oleracea*-based green SeNPs exhibited antimicrobial, antiviral, and mosquitocidal properties [111], while *Urtica dioica*-mediated SeNPs exerted antifungal activity [112]. Additionally, it was reported that SeNPs synthesized using combinations of plant extracts (*Allium cepa*, *Malpighia emarginata*, and *Gymnanthemum amygdalinum*) exhibited antimicrobial activity [116]. Moreover, green-synthesized SeNPs (*Withania somnifera* leaf extract) have been explored for the photocatalytic degradation of methylene blue dye [115].

4.10. Magnesium Nanoparticles

Magnesium oxide nanoparticles (MgONPs) are an attractive material for antimicrobial purposes [117]. Moreover, they have been investigated for other potential applications, including dye degradation, antioxidant, cytotoxic, and antiaging applications [118–120]. The green synthesis of MgONPs has been performed using aqueous extracts from the leaves, flowers, and barks of different plants [118,121,122], when magnesium nitrate ($Mg(NO_3)_2$) [121] and magnesium chloride ($MgCl_2$) [123] have been used as precursors (Table 10). The formation of MgONPs can be identified by a color change from pale green to brown [121], brownish to dark brownish-red [119], and colorless to dark brown [117,123]. Moreover, it has been reported that MgONPs exhibited a UV absorption peak around 280–290 nm and a hexagonal or cubic structure [117–119,122,123].

Table 10. Green synthesis of magnesium nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Magnesium nitrate	*Trigonella foenum-graecum*	Leaf	Aqueous	Spherical	13	Antibacterial	[121]
Aqueous magnesium solution	*Rosmarinus officinalis*	Flowers	Aqueous	Round	<20	Antibacterial	[122]
Magnesium nitrate hexahydrate	*Dalbergia sissoo*	Leaf	Aqueous	Spherical	42	Antibacterial and photocatalytic	[118]
Magnesium nitrate hexahydrate	*Rosa floribunda* charisma	Flowers	Aqueous	Polyhedral	35–55	Antioxidant, antiaging, and antibiofilm	[119]
$MgCl_2$ solution	*Moringa oleifera*	Leaf	Aqueous	Cubic	20–50	Antibacterial	[117]
$MgCl_2$ solution	*Moringa oleifera*	Bark	Aqueous	Spherical	60–100	Antioxidant and antibacterial	[123]
$Mg(NO_3)_2$	*Abrus precatorius*	Bark	Aqueous	Irregular	<100	Antioxidant and cytotoxic	[119]

Vergheese and Vishal [119] demonstrated that spherical MgONPs (13 nm) synthesized using *Trigonella foenum-graecum*, *Xanthomonas oryzae* pv. *Oryzae*, and *Dalbergia sissoo* aqueous leaf extract exhibited antibacterial activity [118]. In general, bioactive compounds such as alkaloids, saponins, flavonoids, phenolics, and terpenoids act as a capping and stabilizing agent during synthesis [120]. However, it must be noted that the pH of the reaction solution may affect the reduction ability of bioactive compounds, mainly owing to the concentration of hydroxyl ions in the medium [118].

Younis et al. [118] found that MgONPs (polyhedral and size of 35–55 nm) synthesized using flower extracts of *Rosa floribunda* charisma exhibited antioxidant, antiaging, and antibacterial activities in a dose-dependent manner against skin pathogens. Additionally, the bark and leaf extracts of *Moringa oleifera* have been investigated for the synthesis of MgONPs with antioxidant and antimicrobial activities [117,123]. Recently, it has been reported that MgONPs with irregular shapes and sizes < 100 nm synthesized by a green approach (*Abrus precatorius* aqueous bark extract) exhibited antioxidant, antibacterial, and cytotoxic activities without toxic effects on zebrafish embryos; moreover, MgONPs exhibited the photocatalytic degradation of methylene blue dye [119].

4.11. Nickel Nanoparticles

Nickel/nickel oxide nanoparticles (NiNPs/NiONPs) have been green-synthesized using aqueous extracts from the leaves, seeds, and flowers of various plants for environmental, antioxidant, antimicrobial, anticancer, and antileishmanial applications [76,124–126]. In the process, nickel nitrate ($Ni(NO_3)_2$) [127], nickel chloride ($NiCl_2$) [128], and nickel sulfate ($NiSO_4$) [129] are the most commonly used precursors (Table 11). During the green synthesis of NiNPs, the color of the reaction mixture changes from green to dark brown [77]. NiNPs were characterized by XRD [Miller index = (110), (111), (200), (220), and (311)], and UV–Vis (surface resonance plasmon of 341 nm and bandgap energy of 1.57 eV) [126,128].

Table 11. Green synthesis of nickel nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Nickel nitrate	*Hordeum vulgare*	Seed	Methanolic	NI	<100	Dye degradation	[127]
Nickel(II) chloride hexahydrate	*Syzygium cumini*	Leaf	Aqueous	Spherical	10	Dye degradation, antioxidant	[128]
NI	*Hammada scoparia*	Leaf	NI	NI	NI	Dye degradation, antimicrobial	[76]
Nickel nitrate	*Senna auriculata*	Flower	Aqueous	Quasi-spherical	53	Dye degradation, antimicrobial	[130]
Nickel chloride	*Lactuca Serriola*	Seed	Aqueous	Spherical	NI	Dye degradation, Antimicrobial	[126]
Nickel nitrate	*Rhamnus virgata*	Leaf	Aqueous	Spherical	24	Antimicrobial. anticancer, antileishmanial, antioxidant	[125]
Nickel(II) sulfate hexahydrate	*Alhagi maurorum*	Leaf	Aqueous	Spherical	20–36	Anticancer	[129]
Nickel nitrate	*Terminalia catappa*	Leaf	Aqueous	Spherical	19	Anticancer	[124]

Yuan et al. [129] synthesized NiNPs (spherical, 20–36 nm) using *Alhagi maurorum* leaf aqueous extract that exhibited cytotoxic and anti-human ovarian cancer activity in a dose-dependent manner [125,128]. Similarly, it was reported that nickel ferrite ($NiFe_2O_4$) nanoparticles (spherical shape, size of 19 nm) synthesized using *Terminalia catappa* aqueous leaf extract exhibited anticancer activity in a dose-dependent manner, possibly through an apoptosis mechanism. The average crystallite size of the Ni nanoparticles was reduced by increasing the volume of the plant extract used [124].

Additionally, *Rhamnus virgata* leaf aqueous extract was used as stabilizing, reducing, and chelating agent during the formation of NiONPs, showing anticancer, antileishmanial, and antimicrobial activities without toxicological effects in human RBCs and macrophages [125]. Ali et al. [126] reported that green-synthesized spherical Ni/NiONPs using the seed extract of *Lactuca serriola* exhibited antimicrobial properties in a strain- and dose-dependent manner due to the capability of the nanoparticles to modify the cell membrane and block the transport channels. Moreover, *Senna auriculata*-mediated and *Hammada scoparia*-mediated NiONPs have exerted antimicrobial properties [76,130].

Furthermore, the seed extract of *Hordeum vulgare* was used to synthesize NiNPs and NiONPs (<100 nm) and was able to degrade methylene blue dye, which exhibited first-order kinetics [127]. Similarly, it was reported that NiONPs green-synthesized using *Syzygium* *cumini* leaf extract with a spherical shape and size of 10 nm exhibited photocatalytic activity against methylene blue and Congo red dyes [128]. Moreover, other plant-based extracts from the seeds, flowers, and leaves from *Lactuca Serriola* [126], *Senna auriculata* [130], and *Hammada scoparia* [76], respectively, have been used for the green synthesis of Ni and NiO nanoparticles for the photocatalytic degradation of crystal violet, methylene blue, and malachite green [76,126,130].

4.12. Sulfur Nanoparticles

Sulfur nanoparticles (SNPs) are biocompatible compounds with a high surface area and catalytic activity, which have great potential for diverse biomedical and agricultural applications [131]. These SNPs have been green-synthesized using aqueous extracts from various plant materials and their parts, including *Rosmarinus officinalis* [132], *Citrus limon* [131], *Aloe vera* [133], *Allium sativum* [134], and *Cinnamomum zeylanicum* [135]. Sodium thiosulfate pentahydrate is commonly used as a precursor for spherical SNPs, ranging from 40 to 69 nm in size [131–135]. After mixing the plant extract and sulfur precursor, a yellow color indicates the formation of SNPs [135]. These nanoparticles agreed with the standard XRD orthorhombic sulfur pattern [133] and exhibited a UV absorption peak of around 245 to 295 nm [132,133] with a zeta potential of −10.4 mV [134].

These SNPs have been used as plant-growth-promoting and nematicidal agents [132,134,135] and are effective antimicrobial agents [131]. Furthermore, SNPs were embedded in a chitosan nanohydrogel for wound-healing applications [131]. Table 12 lists some green-synthesized sulfiur SNPs and their applications.

Table 12. Green synthesis of sulfur nanoparticles using plant-based extracts.

Precursor Used	Plant Name	Part Used	Type of Extract	Shape	Size (nm)	Application	Ref.
Sodium thiosulfate pentahydrate	*Rosmarinus officinalis*	Leaf	Aqueous	Spherical	40	Nematicidal	[132]
Sodium thiosulfate pentahydrate	*Citrus limon*	Leaf	Aqueous	Spherical	40	Antimicrobial, wound healing	[131]
Sodium thiosulfate pentahydrate	*Aloe vera*	Leaf	Aqueous	Spherical	69	No information	[133]
Sodium thiosulfate pentahydrate	*Allium sativum*	Plant	Aqueous	Irregular	45	Plant-growth-promoting	[134]
Sodium thiosulfate pentahydrate	*Cinnamomum zeylanicum*	Bark	Aqueous	Spherical	43–61	Plant-growth-promoting	[135]

4.13. Other Nanoparticles Synthesized by Green Methods

The other nanoparticles synthesized by the green approach using plant-based extracts as capping, reducing, and stabilizing agents include cobalt [136,137], palladium [138], and indium [139,140]. Gingasu et al. [137] used an aqueous extract of ginger roots and cardamom seeds to synthesize cobalt ferrite nanoparticles ($CoFe_2O_4$) with irregular forms and sizes smaller than 100 nm. The authors reported that the Co^{2+} cation distribution was higher than that of Fe^{3+}, possibly associated with the nature of the plant extracts. Similarly, cobalt oxide (Co_3O_4) nanoparticles were green-synthesized using *Populus cilata* aqueous leaf extracts, which exhibited antimicrobial activity [136].

Vinodhini et al. [138] used *Allium fistulous*, *Basella alba*, and *Tabernaemontana divaricate* aqueous leaf extracts to synthesize palladium nanoparticles with photocatalytic activity for Congo red dye degradation. Moreover, palladium nanoparticles exhibited antioxidant and antimicrobial properties in a concentration-dependent manner. Furthermore, palladium nanoparticles prepared with *Tabernaemontana divaricate* leaf extract showed antidiabetic activity in vitro inhibiting the α-amylase enzyme. According to the authors, polyphenol-rich plant-based extracts played an important role in reducing the metal ions and stabilizing the inorganic nanoparticle formation, showing diverse potential applications [137,138]. On the other hand, *Aloe vera* plant extract [140] and *Astragalus gummifer* gums [139] have been used in green synthesis of indium oxide (In_2O_3) nanoparticles, which exhibited good optical properties for further applications [139,140].

5. Advantages of and Challenges in the Green Synthesis of Nanoparticles

Green synthesis has many advantages compared with physical and chemical processes. The inorganic nanoparticles obtained from green synthesis with plant extracts offers an eco-friendly approach since the chemicals used are the bioactive compounds present in the plant [4]. The compounds that reduce metals ions can stabilize the nanoparticles obtained, which avoids the use of different solvents to achieve reduction and capping [141]. Also, operational conditions are mainly environmental, so external energy is unnecessary for the nanoparticles to form. The compounds present in different parts of the plant vary; thus, they allow the synthesis of nanoparticles with interesting morphologies, sizes, and distributions, which opens the possibility of producing a wide catalog of nanoparticles according to their use [142].

On the other hand, some of the challenges for the synthesis of inorganic nanoparticles through plant extracts include low production yield. This can be attributed to the amount and type of bioactive compounds in the extract, which vary depending on the plant and part selected, the growth location, and period of collection. Also, achieving high reproducibility implies a controlled growth environment for plants since factors such as light, nutrient availability, and soil pH impact the production of the metabolites required for green synthesis [4,143]. Although some plants are specific to some regions, availability can also expand the uses of some plants.

6. Conclusions

Green methods that use plant-based extracts as reducing, capping, and stabilizing agents are environmentally friendly, cost-effective, and feasible alternatives for synthesizing inorganic nanoparticles. This approach contributes to the Sustainable Development Goals and circular economy principles. In recent years, various studies have been conducted regarding the green-mediated synthesis of inorganic nanoparticles such as gold, silver, titanium dioxide, zinc, copper, platinum, zirconium, iron, selenium, magnesium, nickel, sulfur, cobalt, palladium, and indium, using plant extracts from the fruits, leaves, roots, stems, barks, seeds, and peel from different plant species. These green-synthesized nanoparticles exhibit interesting properties, including antioxidant, antimicrobial, dye degradation, cytotoxic, analgesic, sedative, wound-healing, and skin-protection properties, as well as being plant-growth promoters and showing potential for sensor development for diverse applications. On the other hand, synthesizing inorganic nanoparticles using plant-based extracts has many challenges that should be solved (low yield and extraction procedures) for their practical production and application. Therefore, further studies are needed to standardize synthesis processes, mainly the extraction conditions that permit narrowing the gap between research laboratories and industry scale-up.

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