Green Synthesized Plant-based Nanotechnology: Cutting Edge Innovation Fostering Sustainability and Revolutionizing Agriculture

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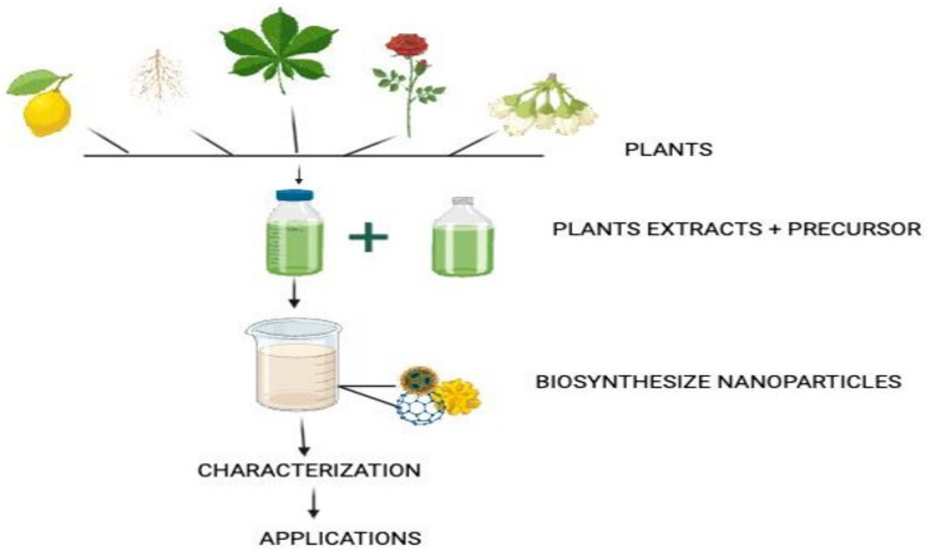
Abstract: The development of smart green chemistry methods for the synthesis of metal nanoparticles (MNPs) has gained significant attention from researchers in the last few years. Due to the widespread usage of nanoscale metal ions in various industries such as health care, engineering, environmental protection, agriculture, etc., the synthesis of these materials is a timely subject and requirement. Currently, most of the nanoscale metals are produced chemically, which has unforeseen consequences such as energy and pollution, as well as health hazards. Numerous studies have been conducted to identify an eco-friendly method for producing the nanoparticles. Metal nanoparticle production using living things is one of the recent approaches that is most frequently discussed. The term "green synthesis of nanoparticles" describes the production of various metal nanoparticles using biologically active substances such as plant parts, microbes, and a variety of waste products like vegetable scraps, peels of fruits wastes, eggshell, farm wastes, and so on. Among these choices, plants seem to be the most ideal source for the potential creation of vast numbers of nanoparticles. Biomolecules present in plant extracts can be used to reduce metal ions into nanoparticles in a single-step green synthesis process, which is rapid, and are more stable. These newly synthesized nanoparticles are usually less expensive, easily available, produce less pollution, and enhance the safety of the environment and human. In the field of agriculture, the synthesis of nano-chemicals has the potential to improve fertilizers (slow-release nano fertilizers), pesticides (nano-pesticides), and nano plant growth regulators. Insects, fungi, bacteria, and weeds are among the plant pests that can be controlled with the use of nano-compounds lately.

Keywords. Green synthesis, metal nanoparticles, plant-based, sustainability, zero hunger, agriculture, life on land

Graphical Abstract



(*Source:* Aquiny)

1 Introduction

The manipulation, manufacturing, and usage of substance with a range in nanometres (nanoparticles) are the key considerations in the academic area of nanotechnology [1]. Nanoparticles (NPs) also called as ultrafine particle is a small particle with a unit measurement of 1-100 nanometres in size. Because they are minute in size they have a variety of applications. In their free state they are quite mobile and they possessed high surface area. Efficiency and sustainability are the main goals of nanoparticle-based technologies. They can work in a variety of fields, including agricultural, engineering, health care and environment clean-up [2]. Depending on their dimension, form, and material properties, NPs can be categorised into a wide range of different categories.There are certain classifications that separate organic and inorganic nanoparticles; the first category consists of dendrimers, liposomes, and polymeric nanoparticles, while the latter category includes fullerenes, quantum dot particles, and metallic nanoparticles [3]. Other categories categorise nanoparticles depending on their carbon, ceramic, semiconducting, or polymeric composition. Additionally, nanoparticles can be categorised as either soft (e.g. nanodroplets) or hard (e.g. Titania - titanium dioxide). Currently, the majority of nanoscale metals are generated chemically, which has unintended effects on energy use and pollution as well as health risks. Despite the fact that nanoparticles may becreated using a variety of physical and chemical techniques [4], their synthesis utilising safe, environmentally friendly biological techniques is appealing, especially if they are meant for invasive uses in medicine [5]. Many studies are currently being conducted on the biosynthesis of metal ion nanoparticles using botanical extracts. These extracts are isolated from plant material with therapeutic qualities.Natural therapeutic plants are being extensively investigated by modern science to determine their potential uses [6]. According to research, nanoparticles made from plants, such as gold (Ag), silver (Au), copper (Cu), platinum (Pt), iron (Fe), zinc (Zn), nickel (Ni), and cobalt (Co) have anticancer, antimicrobial, anti-inflammatory, antioxidant, and antifungal characteristics.Through analytical chemistry instrumental techniques, which entail microscopic and spectroscopic examinations, these metal ion nanoparticles are characterised [7].

This review discusses the creation of nanoparticles through the use of plant extracts. Green chemistry, which blends plants and nanotechnology, is known as plant-based nanoparticle synthesis. Using extracts from plants or using microorganism as potential reducing and capping agents for the synthesizing of nanoparticles is called "green synthesis" [8]. The utilisation of botanical extracts allows for the bio-reduction of metal ions to produce NPs. Plant extract may also be used to create vast quantities of nanoparticles with well-defined dimension and form, are free of contamination, and have a lower environmental impact as compared to the conventional method (chemical or physical method) [9, 10]. The extracts from plant can be used to create nanoparticles more easily than complete plant extracts or plant tissue. A growing amount of research is being done on plant extract-mediated synthesis [11]. Processes for producing nanoparticles using plant extracts are easily scaleable and can be less expensive than the more expensive technologies [9]. It has been demonstrated that plant secondary metabolites, including sugars, protein, terpenoids, polyphenols, alkaloids, and phenolic acids, plays an important role in the reduction of metals ions into nanoparticles and the nanoparticles stability. Plant extracts from the seeds, fruit, and foliage can enhance the properties of nanoparticles and make them more effective in biological applications [12]. Natural substances such as botanical extracts, fungus, microorganisms and algae are used in biological synthesis, a bottom-up synthesis process, to substitute toxic chemicals [13]. A broad spectrum of fields, including biological detectors, changes in the climate and contamination control, sequencing of DNA, power generation, water purification technology, cosmetics, catalysis, pharmaceutical delivery, and the agriculture and food industries, can benefit from green nanoparticle synthesis, which improves biocompatibility, reduces energy consumption, improves stability, and does not use hazardous reagents [14].

Researchers in the field of agriculture have become more interested in nanotechnology during the past few years.Noble metallic nanoparticles (NMNP)-based formulations provide cutting-edge technology to increase agricultural output and reduce the usage of traditional pesticides. In agriculture, nanofertilizers, nanopesticides integrating nanoherbicides, nanocoatings, and radiant delivery systems are being widely utilized [15]. Nanofertilizers ability to regulate the delivery of nutrients with plant absorption can help prevent nutrient losses and lessen the chance of groundwater contamination [16]. Metallic nanoparticles protect plants from multi-drug resistant diseases by acting as antibacterial agents. Numerous agro-based applications have been developed including the diagnosis of plant diseases and the transport of materials using nanoparticles, use nanobiosensors and nanodevices [17]. One of the major challenges the global agricultural business faces is the attack of the pests, which leads to higher losses in the produce. Despite using 3million tonnes of pesticide each harvest and a variety of weedicides, plant pathogens, biological control agents, they still manage to damage more than 40% of all potential food production due to a lack of effective environmental solutions for pest management [18]. People are always looking for new ways to exert control over them. Traditional approaches to pest management, such as integrated pest management, are insufficient, and using synthetic pesticides has negative effects on individuals as well as livestock, reducing fertility in the soil, increasing insect resistance, eradicating biological enemies, polluting the environment, destroying biodiversity. One of the most promising approaches to deal with the issues with utilising traditional chemical pesticides is to use nanotechnology as a substitute approach for pest management. Although there are still many challenges and unknowns, more study is required to enhance their creation, assessment, and regulation [19]. The benefit of adopting nanotechnologies as an alternative strategy is that it is target specific has less damaging side effects to the bio-control agents and pollinators. Furthermore, it provides environmentally friendly, long-lasting nanomaterials that are sustainable [20].

2 Materials and Methods

This paper is structured into several sections, each exploring distinct aspects of nanoparticles (NPs) and their applications. In the initial section, we delve into sustainability principles, which prioritize the responsible use of resources to meet current needs without compromising the well-being of future generations. Green chemistry principles, discussed alongside, advocate for environmentally friendly approaches in designing NPs, minimizing harmful substances' use and promoting resource efficiency. The subsequent section provides an overview of prevalent NP characterization techniques, encompassing aspects such as size, shape, and composition. In the third part, we examine various methods for synthesizing NPs, with a more in-depth exploration of plant-based synthesis in the fourth section. The fifth section specifically delves into metal nanoparticles synthesized from plants. Shifting our focus to applications, the sixth section delves into the diverse uses of plant-based metal NPs. Lastly, in the seventh section; we discuss the valuable role of metal NPs in agriculture, encompassing their utility as nanofertilizers, plant protection agents, and nanopesticides. This review paper draws upon literatures from various reputable sources, including ScienceDirect, Scopus, DOAJ, Google Scholar, PubMed, Research Gate, and other internet resources. It incorporates specific keywords such as Green synthesis, metal nanoparticles, plant-based, sustainability, zerohunger, agriculture and life on land in the title, abstract, and keywords during the systematic search on these primary databases.

3 Fundamentals of Green Chemistry and Sustainability

Less than 15 years ago, the concept of "Green Chemistry" for the sake of "sustainable growth" became extensively studied [21]. Sustainable development can be described as the pursuit of progress that addresses the immediate requirements of today while also ensuring that future generations can fulfil their own needs. This concept holds particular significance for industries rooted in chemistry because of their involvement in pollution and the excessive depletion of natural resources [22]. The general public frequently equates the term "chemical" with risk and toxicity, and chemistry has long been seen as a potentially dangerous discipline [22]. While there exist various ways to reduce these risks through safety measures like protective equipment, when these precautions fail, the potential for hazards and exposure increases. In situations with high levels of risk and failed safety measures, the outcomes can be catastrophic, resulting in injuries or even fatalities. As a result, the development of safe and sustainable chemicals and processes necessitates efforts to minimize inherent hazards to the greatest extent possible and to limit the risk of accidents and harm [21].

4 Characterization of Nanoparticles

Nanoparticles (NPs) have been the subject of significant analysis due to their ease of preparation, high surface-to-volume ratio, diverse optical properties, unique surface chemistry, and relative simplicity in functionalization compared to their bulk counterparts [23]. Precious metal nanoparticles offers the ability to fine-tune their optical properties with ease, allowing for customization of wavelengths based on their size (ranging from 1 to 100 nanometer), shape (nanoshells, or nanorods, nanoparticles,), and composition (including noble alloymetals). This versatility is valuable for applications in imaging and photothermal techniques [24]. The methods frequently used to characterise NPs are UV-Visible absorption spectroscopy, SEM (scanning electron microscopy), TEM (transmission electron microscopy), XRD (X-ray diffraction), DLS (dynamic light scattering), FTIR (Fourier transmission infrared spectroscopy), EDAX (energy dispersive X-ray analysis [23].

SEM and TEM are typically used to describe the morphology and size of NPs [23]. Green synthetic carbon nanotubes were entirely wrapped in polyaniline layers for TEM and SEM examination [25]. TiO2 nanoparticles were generally spherically agglomerated in the 10-30 nm range during TEM investigation. Additionally, a crystalline form was shown by the SAED (Selected area electron diffraction) investigation [26]. UV-Vis spectroscopy was employed to analyze the dimensions and configurations of nanoparticles in a water-based solution [26]. Typically, wavelengths in the range of 300 to 800 nm are utilized to characterize nanoparticles with sizes ranging from approximately 2-100 nm [27].

X-ray diffraction (XRD) is a valuable technique for gaining insights into the structural aspects, size, and phase composition of metallic nanoparticles (MNPs) [28]. By illuminating X-rays into nanomaterials, the diffraction pattern that results can be compared to norms to determine structural features. In the instance of CeO_2 nanoparticles, the XRD analysis revealed distinctive peaks at 2θ angles of 28.51, 33.06, and 47.42, The XRD analysis of CeO_2 nanoparticles revealed unique peaks at 2 angles of 28.51, 33.06, and 47.42, which, respectively, correspond to the crystallographic planes 111, 200, and 220 [29]. Similarly, an XRD investigation by [30] confirmed the existence of a crystalline pattern in Lead (Pb) NPs allowing the determination of a mean particle size of 47 nm using the Scherer equation.

Fourier transmission infrared spectroscopy serves as a valuable tool for discerning the character of functional groups residing on the surface of NPs, playing a pivotal role in their stabilization and reduction [31]. Furthermore, within the 600 to 400 cm^{-1} spectral range, identifiable peaks were ascribed to ZnO [24]. The FTIR characterization of Ag nanoparticles synthesized with *Solanum torvum* leaf extract shows noteworthy peaks at 1648, 1535, 1450, and 1019 cm^{-1} [32]. Of particular interest, the presence of carboxylate ions at 1450 cm^{-1} was implicated as the key factor responsible for stabilizing silver nanoparticles.

The size distribution diffused in liquid and the elemental components of NPs are analysed using the DLS and EDAX, respectively [33].

5 Green synthesizing techniques for producing nanoparticles

Conventional techniques have been used for the synthesis of NPs for a long time; however studies have shown that green ways are more effective because of their lower cost, less failure risks, and simplicity of characterization [34]. In the past decade, green nanotechnology, a significant component of which involves utilizing biological or eco-friendly techniques, has seen considerable growth in the synthesis of nanoparticles. This expansion has been driven by the abundance of diverse biological resources available for this purpose, including fungi [35], bacteria [36], plants [37], algae [38], metabolites from arthropods [39] and enzymes [24]. These nanoparticles that are produced by biosynthesis have variety of applications, like in the field of biomedical science [40], drug-gene delivery [41] skin care products, the environment, food and feed, chemical industry, catalysis, single electron transistors, electronics, light emitters, space sectors, mechanical engineering, the agricultural sector, restoration, and photo-electrochemical industries, to name a few [24].

The "Top Down" and "Bottom Up" methods are the two main methodologies that are generally used in the synthesis of nanoparticles (NPs) (Fig.1). In the top down tactics, NPs are created through size reduction, which is accomplished using a variety of chemical and physical techniques [42]. On the other hand, in the bottom up NPs synthesis, they are generated from smaller units such as molecules and atoms withreduction or oxidation the primary reaction being [14].

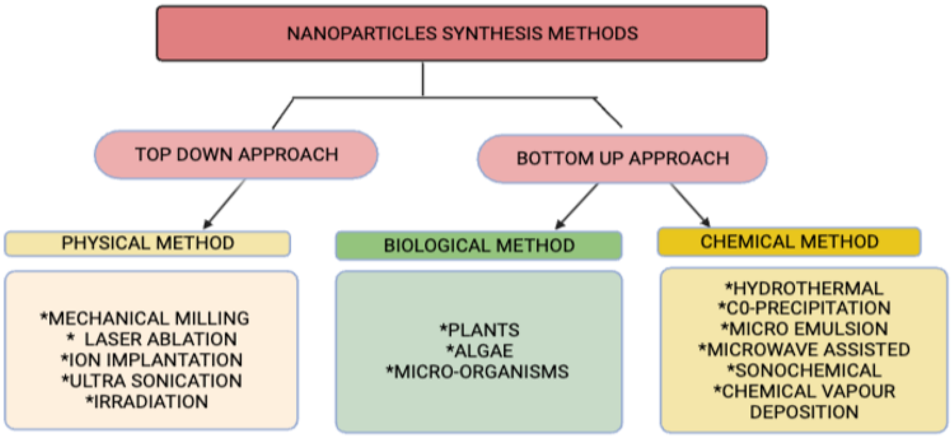


Fig.1. Nanoparticles synthesis methods (Source: Aquiny)

6 Plant based nanoparticles

The biosynthesis of nanoparticles, which uses microorganisms including bacteria, fungi, plants, and actinomycetes to produce clean, ecologically acceptable nanoparticles, has been done using the environmentally accepted "green chemistry" idea. "Green synthesis" is the term used to describe this process [24] (Fig.2). Plants are regarded as nature's inexpensive, high-efficiency chemical factories. Since even minute amounts of metallic residues can be detrimental at extremely low levels, plants have shown exceptional ability in the process of detoxification and deposition. Nanoparticles synthesized from plant extracts are more advantages than the other biological processes like microorganism-based synthesising since they can be carried out through intricate processes for maintaining microbial populations. Plant-based nanoparticle synthesis (Fig.3) has the benefit higher than those of other biosynthetic methods that are comparable to chemical nanoparticles production. Different parts of plants, like fruit, leaves, stems, and roots, have been frequently used for GS-NPS because they contain phytochemical substances [9]. The botanical substances present in plant extracts, such as polyols, terpenoids, and polyphenols, bio-reduce metallic ions [10]. Selected plant parts used in the production of NPs, such as leaves, flowers, or fruits, are properly cleansed with normal water, disinfected with double-distilled water, and then allowed to air dry before utilisation. The sample is dried, and then it is measured and ground. Then, Milli-Q H2O is mixed with plant extract to the required concentration, and the combination is heated while being vigorously agitated. The solution is then filtered using Whatman filter paper [43]. After the isolation, the filtering we then add the appropriate solutions for the NPs we want to synthesis, the colour of the solution begins to change revealing the production of the desired NPS, and we can then separate them [43].
Various plant species, including *Aloe vera* [44], *Desmodium trifolium* [45], *Datura metel* [46], *Pelargonium graveolens* [47], *Azadirachta indica* [48], and *Sorghum bran* [49] have been proposed in scientific literature as potential candidates for the accumulation, detoxification, and phytoremediation of toxic metals. Table.1 presents a compilation of significant plant species utilized in the process of nanoparticle production, accompanied by their respective potential activities. The utilisation of these plants for the purpose of eliminating heavy metals has gained considerable interest due to its substantial capacity to remove pollutants, contaminants, and poisons from wastes in an environmentally sustainable manner. Various nanoparticles, including gold (Ag), silver (Au), zinc oxide (ZnO), and iron (Fe), have been synthesised using an environmentally friendly method. The botanical components present in plant extracts, including polyols, terpenoids, and polyphenols, have the ability to bio-reduce metallic ions [50]. Fig.4 shows the various advantages of green synthesis of nanoparticles from plant sources.

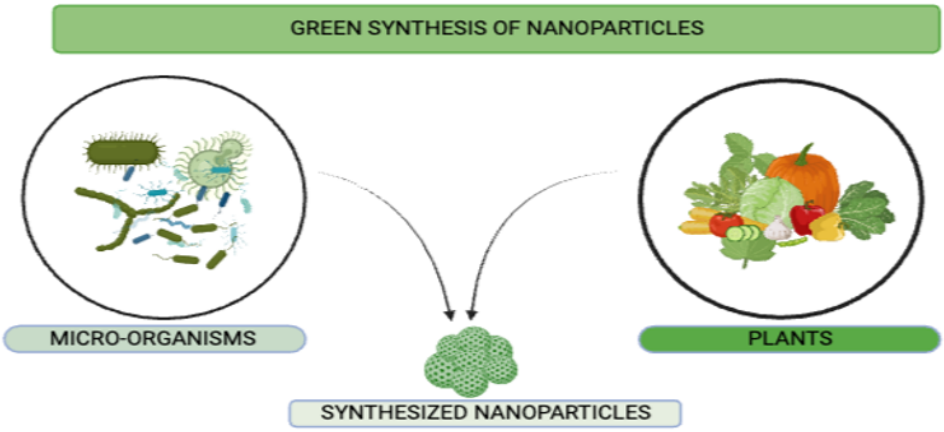


Fig.2. Green synthesis of nanoparticles (GS-NPS) (Source: Aquiny)

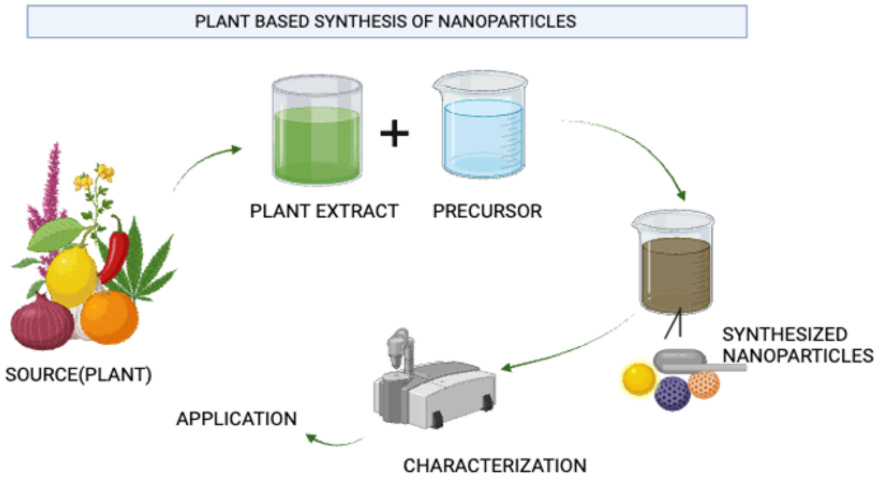


Fig.3. Plant-based nanoparticle synthesis *(Source:* Aquiny)

Table.1. List of plant extracts used for synthesizing nanoparticles (NPs) and their potential activities

Extracts	Nanoparticles	Activities	References
Cymbopogan citrates (Leaves)	Ag	Antifungal against *Candida albicans* and *Aapergillus niger*. Antimicrobial against *Staphylococcus aureus, Klebsiella pnuemoniae, Escherischia coli, Salmonella typhi.*	[51]
Cassia occidentalis (Leaves)	Ag and Cu	Antioxidant, antibacterial acts as a catalysts	[52]
Terminaliaarjuna (Bark)	Cu and Zn	Antihemolytic	[53]
Aegle marmelos, Eugenia jambolana and *Annona muricata* (Leaves)	Au	Anticancer (Breast cancer, MCF-7)	[54]
Plukenetia volubilis (Oil)	Au	Photocatalytic, Antioxidant activity (weak)	[11]
Salvadora persica (Root)	Pd	Stabilizing agent, bioreduction	[55]
Aquilegia pubflora (Leaves)	CeO_2	Antimicrobial, antifungal, protein kinase inhibition, anticancer, antioxidant, antidiabetic	[56]
Mentha arvensis (Leaves)	TiO_2	Antimicrobial	[57]
Nigella sativa (Seeds)	Pt	Antimicrobial	[58]
Annona squamosa (Peel)	Pd	Insecticidal, larvicidal, Acaricidal	[59]
Cuscuta reflexa (All parts)	Ag	Insecticidal	[60]
Capsicum chinense (Leaves)	MNPs, BNPs, TNPs	Insecticidal	[61]
Nopal Cactus (Fruits)	CdS	Insecticidal, antibacterial, and	[62]

		anticancer agent	
Eucalyptus tereticornis (Leaves) and *Pongamia pinnata* (Leaves)	Ag	Insecticidal	[63]
Justicia adhatoda, Pongamia glabra, Ipomea carnea, and *Annona squamosa* (Leaves)	Ag	Insecticidal	[64]
Rosmarinus officinalis L (Leaves)	Fe	Antibacterial and insecticidal	[65]
Carissa edulis (Dried fruit)	Ag2O, ZnO	Insecticidal	[66]
Zanthoxylum nitidum (Leaves)	Ag	Herbicidal	[67]
Zanthoxylum armatum DC (Leaves)	ZnO	Antimicrobial	[68]
Cucumis sativus (Leaves)	Fe	Plant nutrition	[69]
Tagetes erecta L. (Flowers), *Ibiscus sabdariffa* L. (Flowers)	Ag	Antioxidant	[70]
Leucophyllum frutescens (Leaves)	MgO	Photocatalytic	[71]
Neem (Leaves)	Au	Plant protection	[72]
Vitis vinifera, Buchanania lanzan, Phoenix dactylifera (Leaves)	Au	Antimicrobial	[73]
Acacia nilotica (Leaves)	Ag	Antimicrobial, anticancer	[74]
Elaeagnus indica (Leaves)	Se	Antimicrobial and photocatalytic	[75]
Portula caoleracea (Leaves, roots, stem)	CuO	Antibacterial, waste water treatment, catalytic	[76]

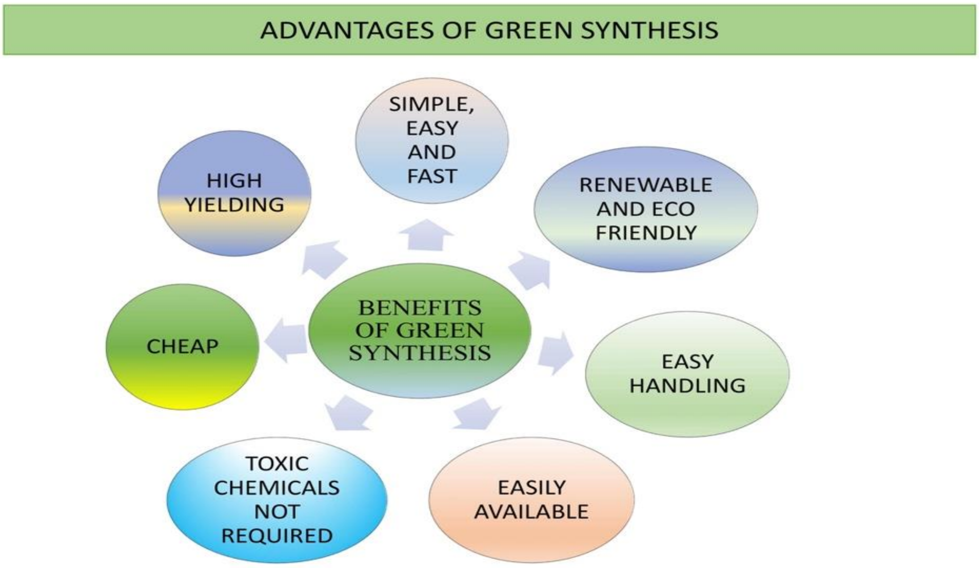


Fig. 4. Benefits of green synthesis *(Source:* Aquiny)

7 Varieties of nanoparticles

A numbers of nanoparticles have been synthesized using green synthesis (GS) methods to date. Common metal NPs (MNPs) synthesized through GS-MNPs and their applications are listed in Table.2. These particles have been characterized through various technique and they are determined by the SEM, TEM, UV Vis-Spectroscopy, UV-DRS, ATR, AFM, EDAX, and FTIR. Discussed below are few of the NPs that are synthesized from plants and their potential applications with examples. The following Fig.5 highlights the different types of nanoparticles which can be synthesized.

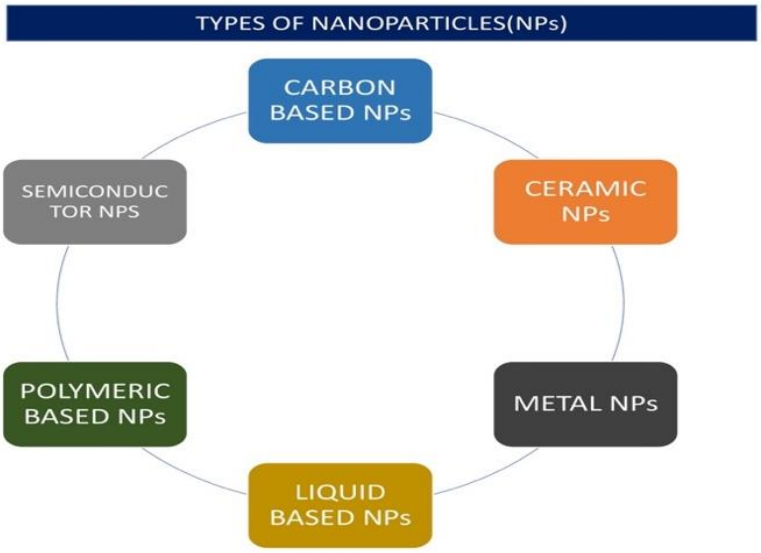


Fig.5. Types of nanopartices *(Source:* Aquiny)

7.1 Gold and Silver NPs (Au NPs andAg NPs)

The manufacture of Ag NPs (spherical, 22–52 nm in size) from *Croton sparsiflorus* leaf extract appeared to be efficient against *Staphylococcus aureus, Escherischia coli, and Bacillus subtilis* [77]. Ag NPs (14-20 nm, spherical) from aqueous extract of *Melia azedarach* leaf possesses antioxidant, antibacterial properties (when tested against *E.coli* and *Bacillus cereus*); wound healing effect, antidiabetic [78]. Au NPs synthesizing from *Cyclopia intermedia* extract possess anti-cancer activity [79]. When tested against gram positive and gram negative bacteria, the AuNPs synthesised from *Aloe vera* leaf broth (9.12 nm) showed they have antibacterial properties [80].

7.2 Iron (Fe) and Iron oxides(FeO)

Fe NP from leaf extract of *Grevillea robusta* has larvicidal potential against *Culex* sp. [81]. FeNPs was synthesized from *Euphorbia milii* (13-21 nm), *Tridax procumbens* (15-32 nm), *Tinospora cordifolia* (43-95 nm), *Datura innoxai* (58-106 nm), *Calotropis procera* (58-91 nm) and *Cymbopogon citrates* (43-342 nm) and the results revealed that they can be used as an alternate source of Fe synthesis [82].

7.3 Zn NPs (Zinc) and ZnO NPs (Zinc oxide NPs)

ZnO NPs was synthesizing from babul leaf extract (*Ocimum basilicum* L. *var. purpurascen*s Benth) reveals that they have antimicrobial activity [83]**.** ZnO synthesized from *Ficus racemosa* L. leaf extract seems to possess antimicrobial, larvicidal and photocatalytic [84]. ZnO (21.49 nm, 25.26 nm) isolated from *Laurus nobilis* L. leaves aqueous extract can be an alternate source for synthesizing Zn NPs [85].

7.4 Cu NPs (Copper)

Cu NPs (10-60 nm) synthesized from *Citrus medica* (L.) (Idilimbu) juice reveals that they possess antimicrobial activity when tested against *Escherichia coli, Fusarium culmorum, Fusarium oxysporum, Fusarium graminearum, Salmonella typhi, Klebsiella pneumoniae, Pseudomonas aeruginosa* and *Propioni bacterium acnes* [86]. Cu NPs (22-27 nm) synthesized from *Rhus coriaria* (L.) fruits extract reveals that they possess antimicrobial activity when tested against the gram positive bacteria [87]. *Thymus vulgaris, Aloe vera, Ginkgo biloba, Carica papaya* are other plants used in the synthesis of Cu NPs [88].

7.5 Ti NPs (Titanium)

Titanium oxide nanoparticles have demonstrated effective antimicrobial properties due to their photocatalytic characteristics, which generate potent antimicrobial radicals like oxides and peroxides and these radicals exhibit broad reactivity against various microbial pathogens. In a study, it is revealed that the Ti NPs (22 nm) synthesized from *Allium eriophyllum* aqueous extract possessed antioxidant, cytotoxicity, and wound healing, antifungal and antimicrobial properties [89]. Titanium dioxide (TiO_2) NPs (20-90 nm) isolated from *Trigonella foenum-graecum* extract shows that they possess antimicrobial activity [90]. Similarly, TiO_2 NPs (32.58 nm) extracted from *Psidium guajava* leaf extract reveals that they possess antioxidant and antibacterial properties when tested against *Staphylococcus aureus and Escherischia coli* [91].

7.6. Mn NPs (Manganese) and MnO NPs

Manganese dioxide nanoparticles (MnO_2 NPs) (32 nm) from *Yucca gloriosa* leaf extract revealed that Mn NPs can be synthesized from its leaf extract and it can be used in many fields like water treatment, water purification [92]. MnOs NPs (17-35 nm, spherical) synthesized from *Gardenia resinifera* leaves shows that the NPs harbour significant antimicrobial activity [93]. Mn NPs (48.10 nm, spherical), isolated from *Ziziphora clinopodioides* leaves revealed that they possess antibacterial, non-cytotoxicity, antifungal, antioxidant properties [94].

7.7.Pd NPs (Palladium) and Pt NPs (Platunum)

Pd and Pt NPs are both expensive metals with high densities. Due to their environmentally friendly sustainable and cost-effective characteristics, both types of plant-derived nanoparticles have garnered the interest of several researchers. Numerous plants such as *Gardenia jasminoides, Cinnamonum* sp. have been employed for the green synthesis of Pt and Pd NPs [95]. Because of its catalytic qualities, Pd NPs are noteworthy and their nanoparticles synthesized from *Pulicaria glutinosa* acts as an excellent catalyst activity towards the Suzuki coupling reaction under aqueous conditions [96]. Likewise, platinum-palladium bimetallic NPs from aqueous leaf extract act as an excellent catalyst [96].

Table. 2. Types of common nanoparticles synthesized from plant extracts and their applications

Metal Nanoparticles (MNPs)	Plants	Size (nm)	Shape	Applications	References
Au (Silver)	*Alternanthera dentate* (Leaves)	50-100	Spherical	Anti-cancer, Antimicrobial, antiviral	[97]
	Camellia sinensis (Leaves)	20-90	Spherical		
	Citrus sinensis (Peel)	10-35	Spherical		
	Aloe vera (Leaves)	50-350	Spherical, triangular		
	Calotropis procera (Peel)	19-45	Spherical		
Ag (Gold)	*Acalypha indica* (Leaves)	15.2	Spherical	Anti-cancer, anti-microbial, biosensor, DNA labelling	[98]
	Cinnamon zeylanicum (Leaves)	45	Spherical		
	Citrus sinensis (Leaves)	35	Spherical		
	Mentha piperita (Leaves)	90-150	Spherical		
	Melia azedarach (Leaves)	79	Irregular		
Zn (Zinc)	*Solanum nigrum* (Leaves)	29	Quasi-spherical	Cosmetics, coating, anti-bacterial, anti-diabetic, anti-cancer, larvicidal	[99]
	Hibiscus subdariffa (Leaves)	12-46	Spherical		
	Rosa canina (Fruits)	<50	Spherical		
	Camellia sinensis (Leaves)	-	Hexagonal wurtzite		
	Mangifera indica (Leaves)	45-50	Nearlyspherical and hexagonal quartzite		
Pt (Platinum)	*Pinus resinosa* (Bark)	6-6	Spherical	Anti-cancer	[100]
	Nigella sativa (Seeds)	3.47	Spherical		
	Ocimum sanctum (Leaves)	2	Irregular structure		
	Mentha piperita (Leaves)	54.3	Spherical		

	Eichhornia crassipes (Leaves)	3.74	Spherical		
Se (Selenium)	*Catharanthus roseus* (Leaves)	32	Spherical	Anti-microbial, anti-cancer	[101]
	Ficus benghalensis (Leaves)	45-95	Spherical		
	Asteriscus graveolens (Fruits)	21	Spherical		
	Allium cepa (Bulb)	245-321	Spherical		
	Gymnanthemum amygdalinum (Leaves)	230-350	Spherical		
Pd (Palladium)	*Aloe barbadensis* (Leaves)	50-350	Triangular, truncated, hexagonal	Biocatalyst	[102]
	Pinus resinosa (Bark)	16-20	Spherical		
	Annona squamasa (Peel)	80	Spherical		
	Cinnamomum camphora (Leaves)	3.2-6	Spherical		
	Moringa oleifera (Peel)	27-29	Spherical		
Cu (Copper)	*Aloe vera* (Leaves)	15-30	Spherical	Anti-microbial, anti-bacterial, anti-viral, bio-film formulation	[103]
	Rosa canina (Fruits)	15-25	Spherical		
	Punica granatum (Seeds)	40-80	Semi Spherical		
	Camellia sinensis (Leaves)	26-40	Spherical		
	Azadirachta indica (L)	48	Cubical		
Fe (Iron)	*Camellia sinensis*(L)	42-60	Spherical	Anti-cancer, molecular imaging, insecticidal	[104,105]
	Moringa oleifera (L)	10-90	Rod		
	Caricapapaya(L)	21.59	Agglomerated		
	Ruellia tuberosa (Leaves)	52.78	Hexagonal nanorods		
	Piper betel (Leaves)	22-35	Cubic		
Si (Silica)	*Thuja orientalis* (Leaves)	33.94	Spherical	Antimicrobial, insecticidal, plant growth	[106]
	Bambusa vulgaris (Leaves Ash)	20	Irregular structure		
	Oryza sativa husk ash	10-30	Irregular structure		
	Oryza sativa straw	14-35	Spherical		
	Fusarium culmorum (Corn cobs husks)	40-70	Spherical		

8 Applications of plant-based nanoparticles

There has been a substantial rise in the number of scientific papers in the subject of nanotechnology over the past ten years. Nanomaterials produced by green synthesis are crucial for the use of nanotechnology in many different industries [23]. Because of its wide range of applications (Fig.6) in many industrial sectors such as chemistry, electronics, markets, and the biological field, there is currently a rising need for nanoparticles on an industrial scale [107]. Numerous in vitro diagnostic applications have made use of nanoparticles [108]. Environmental clean-up can benefit from nanomaterials or their by-products [49]. Surface water, groundwater, and sewage that have been polluted by harmful metal ions, inorganic solutes, organic solutes and microorganism can all be treated using green nanoparticles [109]. In the growing interdisciplinary subject of nanotechnology, silver (Au NPs) and gold (Ag NPs) nanoparticles, which are the most common and have been used in many fields, are of particular relevance for biomedical applications [110]. For instance, for the identification of cancer cells, protein assay, gold nanoparticles have been utilised specifically in cancer therapy. They can serve as biomarkers for diagnostic examinations [111]. They are utilized as precise and powerful heaters to kill cancer cells after cellular absorption. They have the ability to precipitate cell death in B cell chronic lymphocytic leukaemia [112]. Au NPs have been proven to be effective against plasmodial infections, cancer cells, and filariasis and malaria vector larvicidal agents [113]. For example, the AuNPs synthesized from *Albizia lebbeck* (AL) aqueous leaf extract possess anticancer potential against colon cancer (HCT-116) cell line [114]. It was discovered that the Au NPs extracted from *Tamarindus indica* fruit shell extract function as an aid for treating human breast cancer [115]. *Trigonella* seed extract was used to create green synthesis of Ag NPs, which demonstrated their potential for waste water treatment [116]. Due to its numerous uses in biolabeling, antimicrobial, sensors activity, cell electrodes, integratedcircuits, etc., silver nanoparticles have sparked a lot of attention among scientists all across the globe. Due to their antibacterial action, these are useful in many fields, including medicine, food packaging, livestock husbandry, cosmetics and multiple sectors [117]. The Au NPs has shownpromising antibacterial effects against infectious species such *Escherichia coli, Vibrio cholera, Staphylococcus aureus, Bacillus subtilis, Salmonela typhus,* *Pseudomonas aeruginosa* [118]. The TiO_2 NPs synthesized from plants possess a wide array of uses, including agricultural industry, disease diagnostics, fabrication of surgical instruments, and energy production.Pd and Pt NPs are frequently utilised in numerous disease diagnosis without destroying the structure of the genetic material, the deoxyribonucleic acid (DNA) [119]. Some of the Pd NPs demonstrated exceptional antioxidant activities at low nanoparticle concentrations. These nanoparticles also served as nanocatalysts for environmental clean-up. NPs extracted from *Trachyspermum ammi* extract (ajwain), revealed as a potential anticancer agentsagainst breast cells, colon cancer and liver cancer [120]. Nanoparticles work as excellent fertilizers that are environmentally friendly and boost crop productivity as well as substitutes for pesticide in the management and avoidance of plant disease [121].

9 Nanoparticles in Agriculture

Due to their distinctive properties and vast application across numerous disciplines, nanoparticles have attracted a lot of attention in the field of agriculture too [122]. The green synthesis and applications of MNPs in the agricultural industry is to control the slow release of active nano-components including insecticides, vegetative regulators, fertilizers, and herbicides precisely where it is wanted [123]. The extraordinary solubility and stability of these nano-components is the key towards the value of using nanoscale delivery systems in agriculture. By firmly sticking to the plant surface and reducing their dispersion into the atmosphere, these nanoscale carriers improve the efficacy of agricultural chemicals [124]. The green synthesized NPs are also used in nano-biosensors to precisely monitor healthy plant growth and identify plant illnesses [122].

9.1 NPs as nanofertilizers

In order to improve soil quality and agricultural productivity, improved fertilizers known as nanofertilizers are produced using physical, chemical, or biological processes [24]. They possess unique qualities that are absent from traditional chemical fertilizers. Nanoencapsulated fertilizer offers increased solubility, target-specific delivery, and sustained and prolonged discharge of its active ingredients that minimise nutrient loss from soil [125]. Once delivered to a plant physiological system, nanoparticles can interact with the cells and tissues there and cause more modifications. Numerous research have looked at NPs as possible plant stimulators that could promote seed germination, increase the amount of photosynthesis pigments, and boost plant health [126].

9.2 NPs as nanopesticides

Research on nanoscale materials for use in agriculture has gained prominence over the past few decades, with a focus on the creation of novel nano-agrochemicals. Protection of plants is equally important to their growth and productivity. 20% to 40% of crop losses per year are caused by plant pests and diseases [127]. As a result, the new era of nanotechnology employs a variety of methods to control weeds and pests, including the use of nanonematocides, nanopesticides, nanofungicides, and nanoherbicides [128]. The health of ecosystem is disturbed when conventional pesticides are used improperly or excessively, endangering organisms lives [129]. For use in agriculture, nanopesticides are created as nanomaterials that are attached to hybrid substrates specifically, enclosed in matrix, or functionalized nanocarriers for environmental stimulation [130]. The control of pathogenic organisms, weeds, and insect pests can be revolutionised by the use of nanopesticide or nanoherbicide preparations that increase agrochemicals bioavailability, solubility in water, and protection against ecological degradation [24].

9.3 Nanoparticles response towards abiotic plant stresses

Temperature changes, droughts, and salinity stress are just a few of the numerous abiotic stresses that plants are exposed to in nature [131]. NPs have distinctive abilities to reduce abiotic stressors. Regarding noble NPs, the application of Ag NPs enhances seedling development under water-stress circumstances by controlling the production of fermentation-associated proteins and the predominance of the glyoxalase system. Additionally, in response to water stress, the genes encoding pyruvate decarboxylase 2 and alcohol dehydrogenase 1 are upregulated, but they are downregulated after exposure to Ag NPs [132]. This shows that Ag NPs could be able to alter cellular reactions to stress. Ag NPs improve enzymatic mechanisms, alleviate nutrient deficiency, and promote bacteria that stimulate plant development in order to boost plant stress resistance.

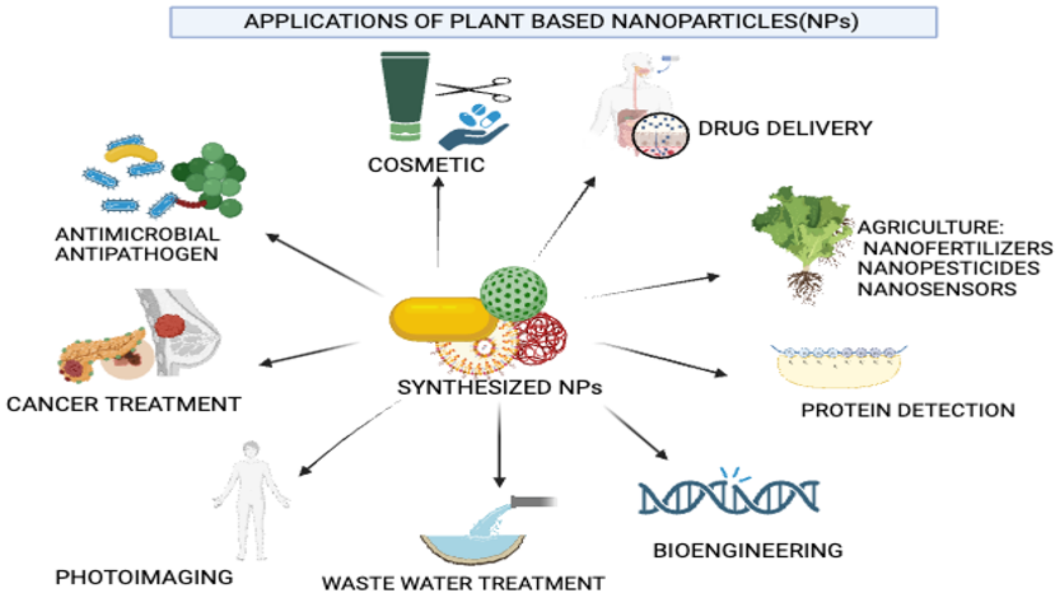


Fig. 6. Applications of plant-based nanoparticles *(Source:* Aquiny)

10 Conclusion

The synthesis of metal nanoparticles (MNPs) has been accomplished using a number of physical, chemical, and biological methods. Issues with nanoparticle stability, aggregation, crystal growth control, shape, size, and size distribution are presently being worked out as most of these approaches are still in the development stage. The creation of Nanoparticles using plant extracts is becoming a significant area of nanotechnology. For biological and medicinal applications where NP purity is crucial, natural resources can be used to produce NPs that are environmentally friendly, affordable, and devoid of chemical pollutants. It has been proven that plant-based nanoparticles are more stable than those derived from other creatures. Plants and plant extracts can deplete metal ions more quickly than fungi or bacteria. For the industrial production of well-dispersed metal nanoparticles, plant extracts are undeniably quicker, safer, and more ecologically friendly than plant biomass or living plants.. In addition to finding and describing the biomolecules responsible for producing nanoparticles, researchers have concentrated on comprehending the physiological and enzymatic mechanisms of nanoparticles formation. Proteins, vitamins, amino acids, polysaccharides, alkaloids and the alcoholic compounds, and are just a few of the compounds found in plants that could be involved in the bio-reduction, synthesis, and stabilisation of NPs. It should be noted that future research may focus on improving reaction conditions and creating recombinant organisms that produce large quantities of the proteins, enzymes, and biomolecules needed for nanoparticle formation and stabilisation. Improved nanoparticle production will result from a better understanding of the biochemical mechanisms or pathways behind plant heavy metal detoxification, accumulation, and resistance. The best way to raise the productivity of these organisms in the synthesis of nanoparticles in the future is by genetic modification of plants with enhanced metal tolerance and accumulation capacity. When compared to other industries, such as the pharmaceutical sector, agriculture is one where nanotechnology has only recently been used. The nanoparticles promotes plant growth and development, regulating plant growth hormones, improves production, and makes sure that there is an ideal amount of nutrients present, balancing antioxidant systems, controlling, and fostering stress tolerance and disease resistance. More research should concentrate on NPs possible environmental risks and the use of eco-friendly, non-cytotoxic nanoparticles with safe exposure threshold values in order to solve the present toxicity issues.

11 References

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