Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 6, 2026

PLANT-MEDIATED GREEN SYNTHESIS OF IRON NANOPARTICLES FOR ADVANCED ENVIRONMENTAL REMEDIATION: MECHANISTIC DESIGN, CHARACTERIZATION, APPLICATIONS, AND SUSTAINABILITY OUTLOOK

*[1]Arshad Ali, [2]Manzar Abbas, [3]Kainat Sarfraz, [4]Ahmed Hussain, [5]Farhan Khan
*[1]Department: Physics, University: Riphah international university Faisalabad
[2]Department: IPMS (Physics), National Chunghwa University of education Taiwan
[3]Department: Physics, Government College University, Faisalabad
[4]Department: Physics, Karakoram international university, Gilgit
[5]Chemistry. Hazara University
*[1]aliarshad12721@gmail.com, [2]manzarabbas13544@gmail.com, [3]kainat.201907177@gcuf.edu.pk, [4]kachoahmed786@gmail.com, [5]farhan.khan408hu@gmail.com

DOI:- https://doi.org/10.5281/zenodo.21219513

Keywords
Iron nanoparticles; Green synthesis; Plant-mediated synthesis; Environmental remediation; Nanotechnology; Phytochemicals; Sustainability; Wastewater treatment

Article History
Received: 25 May, 2026
Accepted: 29 June, 2026
Published: 30 June, 2026

Corresponding Author: * Arshad Ali

Abstract
Industrialization and rapid urbanization have significantly increased the release of toxic pollutants into the environment, resulting in severe ecological degradation and adverse human health effects. Although conventional remediation technologies are widely used, they often suffer from limitations such as high operational costs, secondary pollution, and limited efficiency in removing persistent contaminants. These challenges have accelerated the development of sustainable nanotechnology-based approaches, particularly the green synthesis of functional nanomaterials. Among them, iron nanoparticles (FeNPs) have emerged as promising candidates for environmental remediation because of their high surface reactivity, strong reducing capability, excellent catalytic performance, and magnetic recoverability. Plant-mediated green synthesis has gained considerable attention as an eco-friendly alternative to conventional physical and chemical methods. Plant extracts contain bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, and proteins, which act as natural reducing and stabilizing agents during nanoparticle formation, eliminating the need for hazardous chemicals and supporting green chemistry principles. This review critically examines recent advances in plant-mediated FeNP synthesis, highlighting synthesis mechanisms, the influence of reaction parameters, and characterization techniques used to evaluate physicochemical properties. It further explores the environmental applications of plant-derived FeNPs, including wastewater treatment, degradation of organic dyes, removal of toxic heavy metals, and catalytic oxidation of persistent pollutants. Additionally, the review discusses key challenges related to scalability, reproducibility, environmental safety, and commercialization while emphasizing sustainability. By summarizing current knowledge and identifying future research directions, this review demonstrates the potential of plant-based FeNPs as efficient, sustainable, and environmentally friendly materials for advanced environmental remediation technologies

1. Introduction:

With the rapid development of industries, urbanization, intensive farming methods, and constant population growth, environmental pollution has become one of the most critical concerns of the world. Untreated wastewater from industries has been a major source of contamination of aquatic and terrestrial systems with toxic dyes, heavy metals, pharmaceutical residues, pesticides, and other persistent chemicals that have significantly impacted the environment (Masindi & Muedi, 2018). The pollutants created not only risk biodiversity but also human health due to bioaccumulation, food chain transfer, and long-term environmental persistence. Efficient, sustainable, and environmentally friendly technologies for remediation have therefore become a research priority for researchers around the world (Wang F et al., 2024).

Traditional techniques such as chemical precipitation, coagulation, membrane filtration, adsorption, and advanced oxidation processes have played a significant role in combating pollution (Sales et al., 2020). However, many of these techniques are still limited in terms of their operational costs, energy consumption, the ability to remove contaminants completely, the creation of secondary waste, and their reusability. The need to achieve better remediation efficiency, with reduced environmental impacts, has prompted researchers to seek alternative materials that can deliver these benefits. (Qasim et al., 2023)

Due to the unique physicochemical properties that nanoscale materials have, nanotechnology has quickly become one of the most impactful scientific fields. Nanoparticles typically have dimensions between 1 nm and 100 nm, with extremely high surface area/volumes, high surface reactivity, tunable catalytic properties, and unprecedented optical and magnetic properties. The unique properties of nanomaterials have led to their widespread use in the fields of medicine, agriculture, biosensing, catalysis, renewable energy, and environmental protection. (Aamir et al., 2025)

Due to their high reducing power, magnetic recoverability, low toxicity, ready availability, and low production cost, there is a high interest in the use of iron nanoparticles as a class of engineered nanomaterials with outstanding catalytic activity. (von der et al.,2019) .The iron nanoparticles (nZVI) and iron oxide nanoparticles, specifically magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), have shown a remarkable ability to degrade organic pollutants, immobilize toxic metals, treat industrial wastewater, and remediate contaminated groundwater. The redox reactions and advanced oxidation processes in which they engage make iron-based nanomaterials promising materials for sustainable environmental remediation. (SK et al., 2025)

Iron nanoparticles can be prepared by three methods: physical, chemical, and biological. Typically, physical methods involve using such complex instrumentation that it demands high energy input, while chemical methods often involve the use of hazardous reducing agents and stabilizing chemicals that can produce environmentally harmful by-products. The traditional methods that allow for tight control on the size and morphology of nanoparticles have significant economic and environmental drawbacks that have spurred growing interest in more environmentally friendly methods that meet the criteria of sustainable chemistry (Ali et al., 2016).

Green synthesis process through plants is a promising biological process for the synthesis of iron nanoparticles utilizing renewable natural materials. Plant extracts are rich in bioactive phytochemicals like polyphenols, flavonoids, terpenoids, tannins, alkaloids, proteins, carbohydrates, and organic acids. All the above-mentioned naturally occurring compounds serve as reducing, stabilizing, and capping agents at once, thus helping to form nanoparticles without using toxic synthetic chemicals. Microbial synthesis is generally slower, more complex, and more expensive than plant-based methods, especially when attempting to produce high quantities, and requires sterile culture conditions and complex downstream processing, whereas plants can be cultured in regular conditions and require simpler processing. (Vijayaram S, et al., 2024)

Iron nanoparticles have been successfully synthesized from numerous medicinal plants, crops, fruit wastes, and tea extracts. Camellia sinensis plant, Syzygium cumini, banana peel, mango peel, grape seed, aloe vera, and some medicinal herbs have been found to possess a tremendous potential to produce nanoparticles of various sizes, morphologies, and surface properties. But the above synthesized nanoparticles are greatly affected by various parameters such as plant species, phytochemical content, precursor concentration, extract-to-metal ion ratio, pH, temperature, and reaction time. The understanding of the interaction between these variables is key to optimizing the synthesis of nanoparticles and enhancing their functional performance, as detailed in a recent study (Seedi HR et al 2024).

In recent years, iron-based nanoparticles derived from plants have shown great potential for the treatment of environmental pollution. Due to their high adsorption capacity, catalytic activity, and magnetic separation ability, they are highly effective in removing toxic heavy metals from water, degrading synthetic dyes, removing pharmaceutical contaminants, and purifying industrial wastewater. (Raza et al., 2026). Moreover, they have been shown to improve the degradation of recalcitrant organic contaminants in Fenton and Fenton-like oxidation processes, offering promising potential as environmentally friendly substitutes for traditional remediation methods. (Fasih et al., 2024)

However, there are still several scientific and technological issues to overcome. The constituents of plant extracts vary due to plant chemical variability and hence reproducibility of synthesis; the mechanism of the plant phytochemicals during the formation of nanoparticles is not well known. Moreover, challenges such as those associated with large-scale production, the stability of the nanoparticles, environmental safety, life cycle assessment, and commercial implementation remain to be addressed for broader industrial adoption. (Pande et al., 2024) These constraints must be overcome to enable laboratory-scale research to be applied in the environment as practical technologies.

While many studies have focused on specific components of plant-mediated synthesis of iron nanoparticles, a better overview that combines the synthesis mechanism, critical parameters, and characterization methods, as well as the applications in the environment and sustainability aspects, is still relatively scarce. Hence, this review intends to draw a comprehensive picture of the green synthesis of iron nanoparticles using plants by critically discussing the involved synthesis mechanisms, influential factors for the formation of nanoparticles, physicochemical characterization techniques, remediation applications of plant-mediated green-synthesized iron nanoparticles, scope of current limitations, and future research prospects. The results reported in this review are expected to aid researchers in developing effective, eco-friendly, and commercially viable iron nanoparticle-based technologies for future environmental remediation.

2. Literature Review

2.1 Evolution of Green Nanotechnology:

Nanotechnology is one of the fastest-growing areas in science due to the ability to work with materials at the nanoscale level, where new physicochemical properties appear. The materials in this range (1-100 nanometers) have increased surface reactivity, increased catalytic efficiency, improved mechanical strength, and unique optical, electrical, and magnetic properties. (Emma & Lawrence, 2025). The remarkable properties have given rise to nanotechnology applications in a variety of other fields such as medicine, agriculture, environment, biotechnology, food technology, and renewable energy. With the ever-increasing demand for efficient, sustainable technologies, the research interest in nanomaterials for complex environmental and industrial problems has been further driven by scientific research. (S et al., 2026)

The physical and chemical synthesis techniques were the primary methods used for the preparation of nanoparticles initially. In general, physical methods, such as laser ablation, evaporation–condensation and mechanical milling, result in the creation of nanoparticles of controlled morphology and high purity. Likewise, chemical approaches like chemical reduction, sol–gel synthesis, hydrothermal synthesis, and microemulsion techniques allow to obtain a fine control of the particle size, crystallinity, and composition. Although these are some of the benefits, traditional synthesis methods use expensive instrumentation, high temperatures and pressures, high energy consumption, and/or dangerous reducing or stabilizing agents. The production of toxic by-products and secondary pollutants has also been a concern about their environmental compatibility and sustainability in the long run (Rasel et al., 2026).

With increased awareness of environmental protection and Sustainable Development, researchers are shifting towards alternative methods of synthesis that reduce the ecological impact and preserve the quality of nanoparticles. Such a change has brought forth an interdisciplinary science called green nanotechnology, which combines nanoscience and green chemistry principles. The focus of green Nanotechnology is on the utilization of renewable resources, benign solvents, energy-efficient synthesis methods, and the use of biodegradable reducing agents to obtain environment-friendly nanomaterials. Contrary to traditional synthesis processes, green synthesis aims to minimize waste of chemicals, energy use, and the overall environmental footprint associated with the production of nanoparticles. (Kumar et al., 2024)

The biological method is a more popular way of synthesis among different methods due to its simplicity, safety, and economic viability, in which the plants serve as a catalyst. Plants are a rich source of naturally occurring biomolecules, which can readily reduce metal ions to stable nanoparticles without the use of dangerous chemicals. The plant extracts contain secondary metabolites such as flavonoids, phenolic acids, tannins, terpenoids, alkaloids, proteins, carbohydrates, and organic acids, which play an active role in the formation of nanoparticles. These biomolecules, apart from reducing metal ions, also stabilize newly formed nanoparticles by inhibiting excessive aggregation and enhancing the colloidal stability. In view of this, the synthesis of metallic and metal oxide nanoparticles using plant extracts has emerged as one of the most popular green approaches. (Lakhani KG, et al.,2025)

The rising popularity of green nanotechnology is strongly connected to the worldwide efforts towards sustainable industrial development and environmentally friendly manufacturing. The green synthesis follows several rules of sustainable chemistry, such as the use of renewable biological materials, the reduction of the use of toxic reagents, and the reduction of hazardous waste production. In addition, agricultural residues, fruit peels, medicinal herbs, and other plant-based biomasses are cheap raw materials that are used in waste valorization and the circular bioeconomy. These benefits have made plant-mediated nanotechnology an interesting and promising use in the laboratory and for future industrial production. (Elumalai et al., 2025)

Recent developments have extended the use of green nanotechnology beyond the use of nanoparticles. Recent studies are increasingly aimed at parameter optimization of the synthesis, stabilization of nanoparticles, optimization of catalytic performance, and development of scale-up technologies for commercialization. Meanwhile, the risks of nanoparticles to the environment are a central part of sustainable nanotechnology research, as are environmental risk assessment and life-cycle analysis. The developments show a trend in moving away from the production of nanoparticles to the design of nanotechnology-based materials with an environmental consciousness throughout their life cycle.

Thus, green nanotechnology has become a multi-disciplinary field with the fusion of nanoscience, materials science, environmental engineering, plant biotechnology, and chemistry. As biological synthesis methods continue to evolve and improve, the production of safer, affordable, and more eco-friendly nanomaterials that can help solve the problems of global pollution control, resource conservation, and sustainable industrial development is expected to be enhanced. (Alsaiari NS et al., 2023)

2.2 Iron Nanoparticles: Properties and Environmental Significance:

Iron nanoparticles are among the most promising metallic nanomaterials because of their unique physicochemical properties and excellent remediation potential. In addition to being abundant, relatively cheap, environmentally friendly, and having a remarkable redox activity, iron-based nanomaterials are especially well suited to technologies for the control of pollution. Iron nanoparticles are more applicable in large-scale environmental management due to their lower production price compared to many noble metal nanoparticles, and yield similar remediation capability. (Saif S et al., 2016)

Iron nanoparticles can be in the form of zero-valent iron nanoparticles (nZVI), magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), or hematite (α-Fe_2O_3). Of these, nZVI has been the most extensively studied, due to its high reduction potential and its ability to reduce a wide range of environmental contaminants to less harmful species. Moreover, the iron oxide nanoparticles have magnetic properties that promote swift separation and recovery following remediation methods, enhancing operational efficiency with decreased secondary contamination. (Rasulov, A. et al., 2026)

2.3 Plant-Mediated Green Synthesis of Iron Nanoparticles:

With growing interest in sustainable nanotechnology, sustainable synthesis methods for nanoparticles have been rapidly developed. Of all these methods, the green synthesis using plants as reducing agents is well known as an effective, economical, and eco-friendly method for the synthesis of iron nanoparticles. (Aman Gour &Narendra Kumar, 2019). Plant-assisted synthesis has the advantage of using natural biomolecules to promote the formation of nanoparticles under relatively mild reaction conditions, in contrast to conventional physical and chemical techniques, which often require toxic chemicals, high energy input, and sophisticated laboratory equipment. This environmentally responsible approach aims to reduce hazardous waste generated, as well as promote green chemistry and sustainable manufacturing (Genuino, H et al., 2012).

There are many different phytochemicals present in the plant extracts that actively engage in the synthesis of nanoparticles. Naturally occurring compounds like polyphenols, flavonoids, tannins, terpenoids, alkaloids, proteins, carbohydrates, amino acids, and organic acids have potent reducing and antioxidant properties. (Thatyana M et al., 2023). These biomolecules help in the synthesis process by reducing the iron ions into nanoscale particles through electron transfer reactions. Concurrently, they interact with the surface of the particles and become natural capping and stabilizing agents, suppressing the aggregation of particles and increasing the colloidal stability. The dual function reduces the need for extra synthetic reducing or stabilizing chemicals, increasing environmental safety and economic viability of the procedure. (Villagran et al., 2024)

Another key benefit of plant-mediated synthesis is its ease of operation. The methods involved in preparing plant extracts are relatively simple and are easily followed, so they are accessible to most people. However, microbial synthesis frequently requires sterile culture conditions, continuous culture maintenance, and extended incubation times, thereby complicating production and adding to costs. The plant-based methods are hence a more rapid and practical approach to the fabrication of nanoparticles, especially when substantial amounts of biomass are easily accessible from medicinal plants, crops, or food-processing waste. (Hlatshwayo S et al., 2025)

Many plant species, such as medicinal herbs, fruit peels, seeds, leaves, flowers, and tea extracts, have been reported to synthesize iron nanoparticles. Several plants can create iron nanoparticles, but the differences in their phytochemical content greatly affect the physicochemical properties of the end product. Overall, the plant extracts with higher phenolics and flavonoids content showed higher reducing power, resulting in variations in the size, shape, crystallinity, stability, and catalytic activity of the nanoparticles. Therefore, choosing an appropriate plant source is an important factor in optimizing the quality of nanoparticles for specific environmental applications. (Mihir Herlekar et al., 2914)

The efficiency of plant-mediated synthesis is further determined by several reaction parameters. The dressing plant extract concentration affects the amount of bioactive substances that can be involved in reduction and stabilization, while the concentration of iron salts affects the nucleation and growth of particles. Similarly, the pH of the reaction (acidic and alkaline) has an impact on the ionization of the phytochemicals and the reduction rate, and the temperature will control reaction speed and crystal growth. The other factor that plays a role in particle maturation and stabilization is reaction time. Optimization of these synthesis parameters is critical in achieving nanoparticles that have a reproducible structure and performance. (Christian, Æ et al., 2008)

In recent years, several uses of plant-derived iron nanoparticles in the environment have been recognized. These materials possess high surface reactivity and excellent redox properties, which lead to them being efficient in the degradation of synthetic dyes, adsorption of toxic heavy metals, and transformation of persistent organic contaminants in polluted water. What's more, the magnetic characteristics of iron-based nanoparticles enable the recovery of the nanoparticles after treatment and reuse, reducing the secondary environmental pollution. The above-mentioned properties have led to the development of plant-based iron nanoparticles as a potential source of materials for wastewater treatment, groundwater remediation, soil rehabilitation, and novel oxidation techniques. (Sajna Salim et al., 2025)

While laboratory investigations have led to a promising development, several obstacles currently exist that remain to be overcome for this technology to be widely deployed. Variability in plant species, geographical origin, harvesting season, extraction procedures, and the chemical composition of the plants can be seen in the synthesized nanoparticles. Such inconsistencies make it hard to reproduce and make it difficult to compare independent studies. Moreover, lack of standardized synthesis procedures and optimized large-scale synthesis methods, as well as inadequate long-term stability studies and environmental safety testing, are still major challenges for commercialization.

In general, the plant-mediated green synthesis appears to be a reliable and environmentally friendly method for the synthesis of iron nanoparticles. The conversion of renewable plant resources and environmentally friendly synthesis routes have great potential to improve the general suitability of the production compared to conventional production processes and contribute to sustainable technological development on a global level. The development of production protocols, process optimization, and understanding the mechanisms involved in the plant synthesis of iron nanoparticles will enable the achievement of a standardized method for the plant synthesis of these nanoparticles for future use in environmental remediation. In addition, it is crucial to carry out an extensive environmental risk assessment to encourage the use of plant iron nanoparticles in environmental remediation.

Sr. No.	Plant	Part	Shape	Size	Applications	Reducing/ Capping Agents	References
01	Camellia sinensis (green tea)	Leaves	Irregular agglomerates	10-100 nm	Antioxidant	polyphenols	[15]
02	Green tea	Tea Extract powder	Irregular clusters	40-60 nm	Antimicrobial	polyphenols	[16]
03	Oolong tea	Tea extract	Spherical	40-50 nm	Fenton catalyst, degradation of dye (MG)	Polyphenols/ caffeine	[17]

2.4 Mechanistic Design of Plant-Mediated Green Synthesis of Iron Nanoparticles

The plant-mediated synthesis of Fe nanoparticles is a complex biochemical reaction that occurs when metal ions react with the phytochemicals present in plant extracts. The plant-assisted synthesis option does not use synthetic reducing agents and stabilizers compared to the conventional synthesis methods. These compounds not only lower the pH of the solution and thereby convert Fe3+ to Fe0, but they also control nucleation, growth of the particles, stabilization of the surface, and long-term stability. These processes affect the physicochemical properties and environmental performance of the synthesized nanoparticles. (Soomro, R.et al., 2025)

2.4.1 Role of Phytochemicals in Nanoparticle Formation

A broad spectrum of secondary metabolites is present in plant extracts, which play an active role in the synthesis of nanoparticles. Polyphenols, flavonoids, tannins, terpenoids, alkaloids, proteins, amino acids, carbohydrates, and organic acids have functional groups that can donate electrons in redox reactions. The presence of hydroxyl, carbonyl, carboxyl, and amino groups helps these molecules transform dissolved iron ions into solid nanoparticles. The concentration and composition of these phytochemicals vary depending on the plant species, giving rise to differences in the size, shape, crystallinity, and catalytic activity of nanoparticles. Therefore, the phytochemical profile of the plant extract selected is of crucial importance as it determines the efficiency of synthesis and the quality of the product. (Zuhrotun A et al., 2023)

2.4.2 Reduction of Iron Ions

The first step in the synthesis of nanoparticles is to reduce the precursor ions of iron to lower oxidation states by transferring electrons in the system using biomolecules derived from plants. Polyphenolic compounds and flavonoids, in particular, are good reducing agents due to their high antioxidant activity. The electron donation during the reaction converts dissolved iron ions to elemental iron or iron oxide nanoparticles. At the same time, a redox process occurs as the phytochemicals get oxidized without the need for the use of toxic chemical reducing agents. This is a naturally driven reduction mechanism that will be the basis for environmentally friendly synthesis of nanoparticles. (Great Iruoghene Edo et al., 2025)

2.4.3 Nucleation and Particle Growth

After the ions have been reduced, the newly created iron atoms start to coalesce to form small and energetically stable nuclei. These nuclei act as the main nuclei for further development of nanoparticles. The particles are growing slowly as more and more reduced iron atoms are added onto the growing particles until the particles are in a state of thermodynamic equilibrium. The nucleation rate, which is the rate at which particles are formed, has a significant effect on the size and shape of the nanoparticles. Generally, faster nucleation will lead to more particles with smaller sizes, while slower nucleation and longer growth times will lead to bigger and less uniform nanoparticles. Hence, the key to ensuring the balance among these processes is crucial to obtaining reproducible physicochemical properties of nanoparticles. (Liu Y et al., 2024)

2.4.4 Stabilization and Surface Capping

Newly synthesized nanoparticles have high surface energy and are prone to aggregation and oxidation. Biomolecules from the plants bind to the surface of the nanoparticles, which coat the surfaces and act as caps. This biological coating works to further decrease attractive forces between neighbouring nanoparticles and thus prevent too much aggregation and enhance the colloidal stability. Furthermore, surface-bound phytochemicals prevent the rapid oxidation of nanoparticles during storage and environmental use. The better the stabilization, the higher the dispersion of the particles, the longer their shelf life, and the better the catalytic performance during environmental remediation processes. (Zhou, Fang et al.,2023)

2.4.5 Factors Influencing the Mechanistic Process

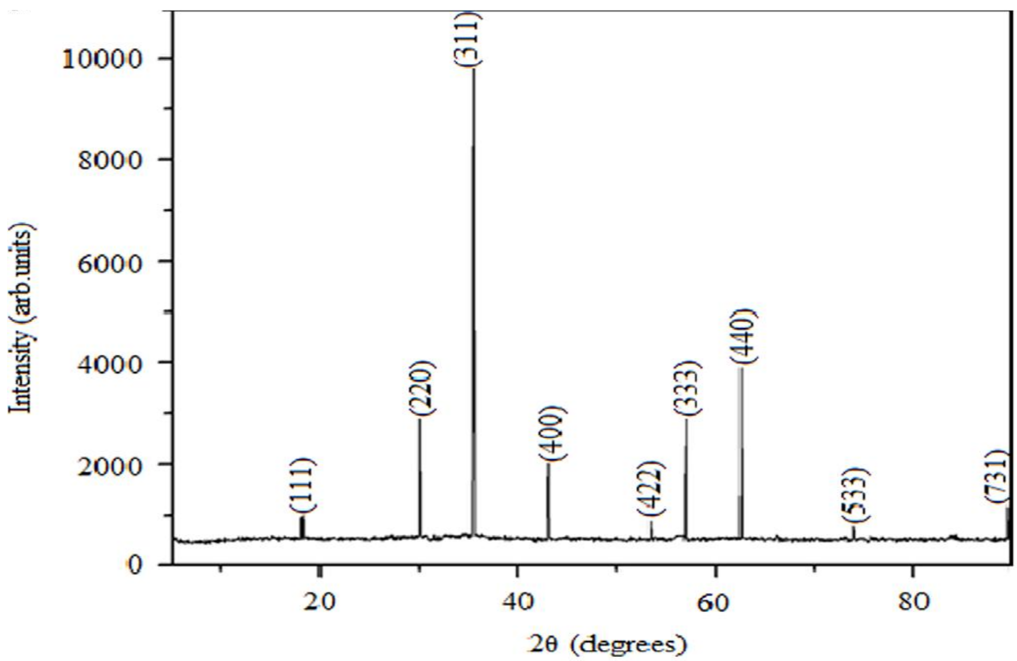
Reaction parameters are factors that control the efficiency of plant-mediated nanoparticle synthesis. The availability of reducing and stabilizing molecules in the extract is related to the phytochemical composition of the extract, while the concentration of the iron precursors will directly influence the nucleation and yield of nanoparticles. The pH of the reaction determines the ionization of functional groups and affects the rate of reduction, and the temperature determines the mobility of molecules, the rate of reaction, and the growth of the crystals. Likewise, reaction time determines the completion of reduction, particle maturation, and stabilization. These parameters need to be optimized so that nanoparticles can be synthesized in a controlled manner, with reproducible properties, which are appropriate for use in environmental applications. (Shafie et al., 2025)

2.4.6 Mechanistic Significance for Environmental Remediation

Plant-mediated synthesis directly affects the environmental performance of the nanoparticles made of the iron. Generally, the smaller the particle size, the greater the surface area and the greater the structural stability; the better the adsorption capacity, catalytic activity, and redox behavior of the nanoparticles. Efficient surface capping also results in good particle dispersion, which enables interaction with environmental contaminants and thereby promotes pollutant degradation and heavy metal removal. It is hence important to understand the correlation between the synthesis mechanisms and the properties of the nanoparticles to design highly efficient nanomaterials for wastewater treatment, remediation of groundwater, soil restoration, and advanced oxidation processes.

In general, the process of plant-mediated synthesis is a well-coordinated reduction, nucleation, growth, and stabilization process controlled by naturally occurring phytochemicals. These biomolecules work together to produce iron nanoparticles with no toxic chemicals and enhance the stability of the particles and their environmental compatibility. Ongoing research on the molecular mechanisms of phytochemical-assisted synthesis will help to develop standardized, reproducible, and scalable methods for production that can be used in the development of future environmental remediation technologies. (Ebrahiminezhad A et al., 2018)

Figure 1. Proposed mechanism of plant-mediated green synthesis of iron nanoparticles



3. Characterization of Green-Synthesized Iron Nanoparticles:

Necessary for the assessment of the successful synthesis of plant-mediated iron nanoparticles and their functional properties, accurate characterization is a critical step. The environmental performance depends directly on the physicochemical properties of nanoparticles, such as particle size, morphology, crystallinity, elemental composition, surface chemistry, and colloidal stability. In this sense, it is common to use a set of techniques that can provide a complete picture of the structure and behaviour of nanoparticles. This method not only ensures the successful production of nanoparticles but also offers insights into optimizing synthesis parameters and assessing the potential for environmental remediation. (Ahmed et al., 2025)

3.1 UV–Visible Spectroscopy:

One preliminary analytical tool used to monitor the formation of nanoparticles is UV–Visible (UV–Vis) spectroscopy. In the synthesis process, the reduction of the iron ions is sometimes accompanied by a visible color change of the reaction mixture, which is an indication of the formation of the nanoparticles. The formation of absorption bands demonstrates successful synthesis and can be used to trace the progress of a reaction under various experimental conditions. UV–Vis spectroscopy is a quick and easy analysis but is typically combined with other methods to provide detailed structural information. (Abbas et al., 2026)

3.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform InfraRed (FTIR) spectroscopy is generally used to detect the presence of biomolecules (plants) used for the synthesis of nanoparticles containing functional groups. The presence of polyphenols, flavonoids, proteins, and organic acids is indicated by changes in the FTIR spectra before and after the synthesis, which are supposed to participate in the reduction and stabilization of the iron nanoparticles. This analysis can give insight into how phytochemicals interact with the surface of the nanoparticles and also validate the role of natural capping agents in enhancing the stability of the nanoparticles. (Pasieczna et al., 2025)

3.3 X-ray Diffraction (XRD)

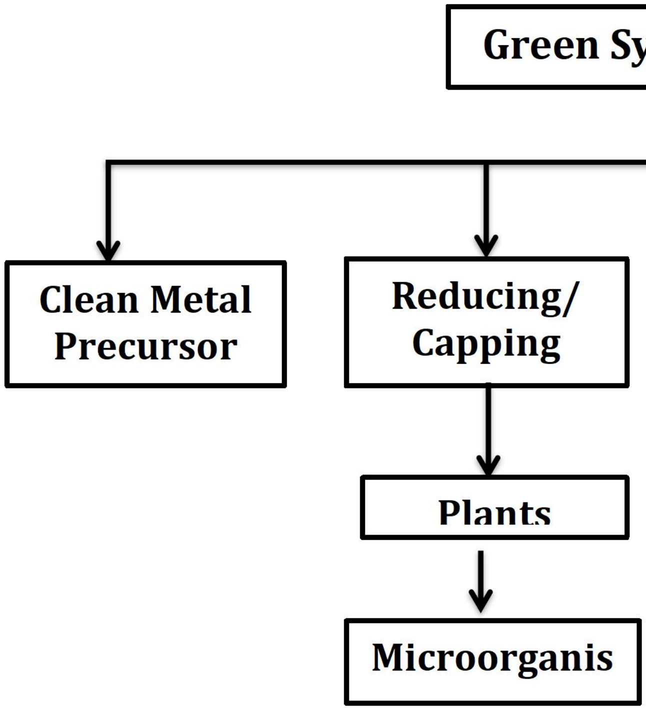
X-ray Diffraction (XRD) is one of the most reliable analytical techniques to investigate the crystalline structure and phase composition of green-synthesized iron nanoparticles. It involves the diffraction of X-rays by the regularly arrayed atomic planes of crystalline material. Incident X-ray beam gets diffracted at certain diffraction angles when constructive interference takes place, creating unique diffraction peaks that are characteristic of every crystalline phase. Therefore, XRD is widely used to verify the synthesis of nanoparticles, study the crystallinity of the nanocrystals, determine the crystal phases, and measure the structural purity of the nanoparticles.

The diffraction phenomenon obeys Bragg's Law, that is, the relationship between the incident X-ray beam and the crystal lattice:

[n\lambda = 2d\sin\theta]

In which n is the diffraction order, λ is the wavelength of the incident X-rays, d is the interplanar spacing between two adjacent crystal planes, and θ is the diffraction angle. Constructive interference produces distinct diffraction peaks that inform about the crystal structure of the synthetic nanoparticles when this condition is met.

In addition to confirming the crystallinity of the nanoparticles, XRD is also commonly used to estimate the average crystallite size of nanoparticles from the nanoparticles by using the Debye–Scherrer equation:

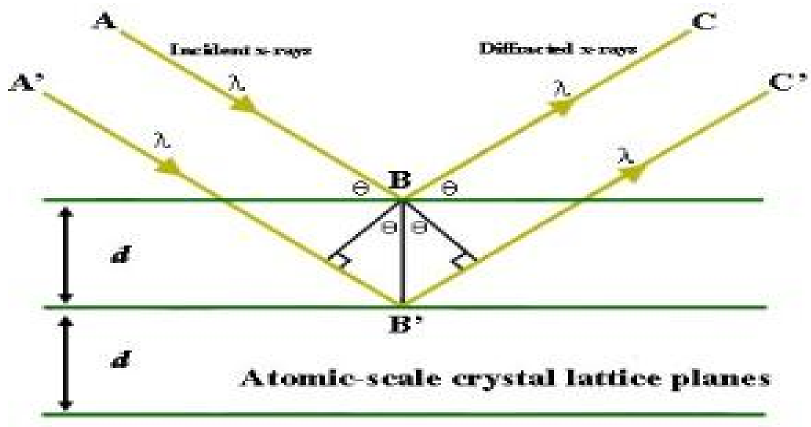


Here, D is the average crystallite size, K is the shape factor (typical value is 0.9), λ is the X-ray wavelength, β is the full width at half maximum (FWHM) of the diffraction peak, and θ is the Bragg angle. The equation allows scientists to determine the size of crystals as small as a nanometer and compare the physical properties of crystals produced in different experiments.

For plant-mediated synthesis, XRD data are valuable evidence for the successful synthesis of the iron nanoparticles or iron oxide nanoparticles, as it is compared with the standard crystallographic database. The varying peak intensity and width also provide information regarding crystallinity, crystal defects, and particle size. The XRD, however, mostly provides information on the structural characteristics of the nanoparticles, and is therefore normally used in combination with microscopic techniques like SEM and TEM to get a complete picture of the morphology and size distribution of the nanoparticles.

In conclusion, XRD is an invaluable tool for characterizing the structural properties of green-synthesized iron nanoparticles and correlating the synthesis parameters with the performance of the nanoparticles in environmental remediation.

Figure 3. Illustration of Bragg's Law showing X-ray diffraction from crystal planes.



3.4 Scanning Electron Microscopy (SEM)

The surface morphology and microstructural features of the iron nanoparticles prepared using green route methods have been characterized using the Scanning Electron Microscopy (SEM) technique. Unlike optical microscopy, SEM is based on the use of a focused stream of high-energy electrons that are scanned across the surface of the sample, creating high-resolution images with excellent depth of field. Secondary and backscattered electrons are created by the interaction of the electron beam with the sample and are detected to build up detailed images of the surface.

SEM analysis gives important information on the shape, surface roughness, level of aggregation, and distribution of particles in the form of nanoparticles. The adsorption behaviour, catalytic efficiency, and environmental performance of iron nanoparticles are directly affected by these morphological features. The more uniform the distribution of the nanoparticles with less aggregation, the more surface area, and the more reactive they are, the better they will be for contaminant removal.

While SEM provides high surface resolution, its resolution in the measurement of individual nanoparticles is less than that of Transmission Electron Microscopy (TEM). Thus, SEM is often used in conjunction with TEM and elemental analysis for a complete understanding of the morphology and composition of nanoparticles.

3.5 Energy-Dispersive X-ray Spectroscopy (EDS)

Elemental composition of green-synthesized Fe nanoparticles is determined using Energy-Dispersive X-ray Spectroscopy (EDS), commonly used in conjunction with SEM. Characteristic X-rays are emitted when the electron beam interacts with the sample, which allows the determination of the constituent elements. EDS validates the presence of iron and other related elements, thus verifying the composition and functionalization of the nanoparticles' surfaces. (Joseph Goldstein, 2003)

3.6 Dynamic Light Scattering (DLS) and Zeta Potential

Dynamic Light Scattering (DLS) is used for the determination of the size and size distribution of the nanoparticles in suspension, and zeta potential analysis is used to determine the surface charge and colloidal stability of the nanoparticles. The techniques play a crucial role in the dispersion, aggregation behaviour, and stability of nanoparticles, directly affecting their application in environmental remediation. (Rodriguez-Loya, 2024)

3.7 Importance of Characterization

In order to confirm the synthesis of nanoparticles and to gain insight into their physicochemical properties, comprehensive characterization is needed. The information from combined UV–Vis, FTIR, XRD, SEM, EDS, DLS and zeta potential analysis can be relied on for obtaining reliable information on particle size, morphology, crystallinity, elemental composition, surface chemistry and stability. These methods work synergistically to optimize green synthesis methods and improve the use of iron nanoparticles in environmental remediation. (Ntolia, A, 2025)

4. Environmental Remediation Applications of Plant-Mediated Iron Nanoparticles

The plant-made iron nanoparticles are attractive nanomaterials for environmental remediation due to their high surface area, significant redox activity, magnetic properties, and environmentally friendly synthesis. Additionally, the presence of bioactive phytochemicals on the surface of the nanotechnology also results in an effective adsorption capacity and catalytic performance, with the reduction of secondary environmental pollution. As a result, a variety of inorganic and organic pollutants are being thoroughly studied for their removal from aqueous and soil media by these nanoparticles. (Singh J et al., 2018)

4.1 Removal of Heavy Metals

Heavy metal contamination, which is a serious environmental problem because of the persistence and toxicity of metals like lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As), is a major environmental concern. It is found that the green synthesized iron nanoparticles are very effective in removing these contaminants through adsorption, reduction, co-precipitation, and surface complexation processes. They have a high surface reactivity and contain abundant active sites for binding toxic metal ions, which will decrease their mobility and bioavailability. From the viewpoint of conventional adsorbents, plant-mediated iron nanoparticles provide greater removal efficiency with reduced formation of secondary pollutants. (Mohamed HI et al., 2025)

4.2 Degradation of Organic Dyes

Synthetic dyes from textiles, leather, paper, and printing are among the largest contributors to water pollution. The dye degradation ability of plant-synthesized iron nanoparticles is outstanding against dyes like methylene blue, methyl orange, Congo red, and rhodamine B. These nanoparticles enhance redox reactions and advanced oxidation processes for the conversion of complex dye molecules to simpler and less toxic molecules. They are also easily synthesized in an environmentally friendly way, demonstrate a high catalytic efficiency, and are therefore promising alternatives to conventional wastewater treatment technologies. (Jara YS et al., 2024)

4.3 Wastewater Treatment

The green synthesized iron nanoparticles are very useful in treating the industrial and municipal wastewater contaminated with mixed organic and inorganic contaminants. Their multifunctional properties allow them to adsorb, catalytically degrade, and reduce pollutants simultaneously, leading to better water quality. Further, the magnetic properties of the iron nanoparticles allow for easy recovery and reuse following treatment, promoting sustainability and lowering operational costs. The characteristics contribute to the efficiency and environmentally friendly wastewater treatment systems. (Nkosi ET al.2024)

4.4 Groundwater and Soil Remediation

Industrial discharge, agricultural chemicals, and faulty waste disposal practices can lead to contamination of groundwater and soil, which has serious impacts on ecosystems and human health. In situ remediation of contaminated soils and groundwater using plant-derived iron nanoparticles for in situ reduction and immobilization of hazardous pollutants has been demonstrated to be promising. They are so small that they penetrate porous media and can be so reactive that they rapidly transform toxic contaminants into less harmful ones. The benefits of using iron nanoparticles for contaminated environmental remediation make them an interesting material. The advantages of using iron nanoparticles for contaminated environmental remediation make them an interesting material. (Galdames et al., 2020)

4.5 Removal of Emerging Contaminants

Pharmaceuticals, pesticides, personal care products, and endocrine-disrupting compounds are becoming common in the water, and their presence has led to worldwide environmental concerns. The catalytic activity and high surface area of the green-synthesized iron nanoparticles (IONPs) make them promising for the degradation and adsorption of these emerging contaminants. The combination of iron nanoparticles with advanced oxidation technologies further improves the capability of removing contaminants and supports sustainable water purification technologies. (Cardoso et al., 2021)

4.6 Antimicrobial Applications

Besides pollutant removal, plant-mediated iron nanoparticles have antimicrobial properties against various pathogenic microorganisms. By interacting with microbial cell membranes, they cause oxidative stress, disrupt the membrane, and cause damage to the inside of the cell, thus inhibiting the growth of microbes. These properties have the benefit of enhancing the disinfection and environmental sanitation of wastewater and mitigating the reliance on traditional chemical disinfectants. (Wang L et al., 2017)

4.7 Sustainability Outlook:

Although research in the laboratory has made great strides, there are a number of barriers that hinder the use of plant-mediated iron nanoparticles in a wider range of applications. Some research gaps include variability in plant phytochemical composition, standards for synthesis protocols, insufficient scale-up of production, and inadequate knowledge of long-term environmental impacts. Further research is needed to optimize synthesis conditions, enhance the stability and reusability of the nanoparticles, perform life cycle assessments, and assess the ecological risks under real environmental conditions. The solutions to these challenges would pave the way for the commercialization of sustainable iron nanoparticles for advanced environmental remediation.

5 Conclusion:

Green synthesis by plants represents an environmentally friendly and sustainable method to synthesize iron nanoparticles, which are very promising in the field of advanced environmental remediation. The use of phytochemicals from plants as reducing and capping agents is a safer, cost-effective, and energy-efficient alternative to traditional synthetic or chemical ways of making the products with less use of hazardous chemicals. A variety of characterization methods, such as UV–Visible spectroscopy, FTIR, XRD, SEM, EDS, and DLS, are essential to the confirmation of nanoparticle formation and the evaluation of the physicochemical properties of nanoparticles. These properties are the main factors affecting the efficiency of the removal of heavy metals, degradation of organic dyes, wastewater treatment, and remediation of contaminated soil or groundwater by iron nanoparticles.

Though promising results have been obtained on a laboratory scale, issues regarding standardization of the synthesis, large-scale production, stability, and safety to the environment have yet to be solved before commercialization. Scale-up green synthesis methodology, comprehensive risk assessment, and field applications will be the focus of future research to enhance the practical applications of these nanomaterials. In summary, plant-mediated iron nanoparticles are promising for developing sustainable remediation technologies and are anticipated to be more and more important to solve global environmental pollution in the future, which is also conducive to the principle of green chemistry and sustainable development.

References:

1. Masindi, V., & Muedi, K. L. (2018). Environmental contamination by heavy metals. In Heavy metals. IntechOpen. https://doi.org/10.5772/intechopen.76082
2. Wang, F., Xiang, L., Leung, K. S.-Y., Elsner, M., Zhang, Y., Guo, Y., Pan, B., Sun, H., An, T., Ying, G., Brooks, B. W., Hou, D., Helbling, D. E., Sun, J., Qiu, H., Vogel, T. M., Zhang, W., Gao, Y., Simpson, M. J., ... Tiedje, J. M. (2024). Emerging contaminants: A One Health perspective. Innovation, 5(4), 100612. https://doi.org/10.1016/j.xinn.2024.100612
3. Sales da Silva, I. G., Gomes de Almeida, F. C., Padilha da Rocha e Silva, N. M., Casazza, A. A., Converti, A., & Asfora Sarubbo, L. (2020). Soil bioremediation: Overview of technologies and trends. Energies, 13(17), 4664. https://doi.org/10.3390/en13174664
4. Ali, Q., Zia, M. A., Kamran, M., Shabaan, M., Zulfiqar, U., Ahmad, M., Iqbal, R., & Maqsood, M. F. (2023). Nanoremediation for heavy metal contamination: A review. Hybrid Advances, 4, 100091. https://doi.org/10.1016/j.hybadv.2023.100091
5. Sohail, A. (2025). Progress in nanomaterials: Synthesis, characterization, and applications. Next Nanotechnology, 8, 100263. https://doi.org/10.1016/j.nxnano.2025.100263
6. von der Heyden, B., Roychoudhury, A., & Myneni, S. (2019). Iron-rich nanoparticles in natural aquatic environments. Minerals, 9(5), 287. https://doi.org/10.3390/min9050287
7. Begum, S. K., Shabnam, D., Haque, N., Alam, M. J., Ferdous, J., Nur, U. J. B., Fatema, K., Shabiha, R. J., Clarke, R. J., Chowdhury, P., & Uddin, M. N. (2025). Green synthesis of magnetite (Fe_3O_4) and hematite (Fe_2O_3) nanoparticles using Moringa oleifera and Psidium guajava leaf extracts for sustainable applications. Scientific Reports, 15(1), 36465. https://doi.org/10.1038/s41598-025-21603-4
8. Ali, A., Zafar, H., Zia, M., Ul Haq, I., Phull, A. R., Ali, J. S., & Hussain, A. (2016). Synthesis, characterization, applications, and challenges of iron oxide nanoparticles. Nanotechnology, Science and Applications, 9, 49–67. https://doi.org/10.2147/NSA.S99986
9. Vijayaram, S., Razafindralambo, H., Sun, Y. Z., Vasantharaj, S., Ghafarifarsani, H., Hoseinifar, S. H., & Raeeszadeh, M. (2024). Applications of green synthesized metal nanoparticles: A review. Biological Trace Element Research, 202(1), 360–386. https://doi.org/10.1007/s12011-023-03645-9
10. Kasture, S., Adnaik, P., Shirguppe, A., & Adnaik, R. (2026). Phytochemical-assisted green synthesis of iron nanoparticles and their emerging biomedical applications. International Journal of Pharmaceutical Sciences, 4(5), 6407–6416. https://doi.org/10.5281/zenodo.20361236
11. El-Seedi, H. R., Omara, M. S., Omar, A. H., Elakshar, M. M., Shoukhba, Y. M., Duman,

H., Karav, S., Rashwan, A. K., El-Seedi, A. H., Altaleb, H. A., Gao, H., Saeed, A., Jefri, O. A., Guo, Z., & Khalifa, S. A. M. (2024). Updated review of metal nanoparticles fabricated by green chemistry using natural extracts: Biosynthesis, mechanisms, and applications. Bioengineering, 11(11), 1095. https://doi.org/10.3390/bioengineering11111095

12. Raza, N., Anwar, A., Shoaib, A., Khan, S., Intisar, A., Habib, M. S., & Irshad, F. (2026). Catalyzing innovation: Exploring the potential of eco-friendly synthesized magnetic iron oxide nanoparticles for heavy metals removal from water. Discover Nano, 21(1), 56. https://doi.org/10.1186/s11671-025-04342-3
13. Haider, F. U., Zulfiqar, U., Ain, N. ul, Hussain, S., Maqsood, M. F., Ejaz, M., Yong, J. W. H., & Li, Y. (2024). Harnessing plant extracts for eco-friendly synthesis of iron nanoparticles (Fe-NPs): Characterization and their potential applications for ameliorating environmental pollutants. Ecotoxicology and Environmental Safety, 281, 116620. https://doi.org/10.1016/j.ecoenv.2024.116620
14. Pande, D. (2024). Sustainable nanoparticle production: Challenges and innovations. Journal of Nanoscience Current Research, 9, 252.
15. Lawrence, E. (2025). Nanotechnology and its applications in science and engineering.
16. Rabani, M. S., Shrivastav, M., Fayaz, M., et al. (2026). Mechanistic advances in microbial nanobiotechnology and their applications in sustainable agriculture, environment, and biomedicine. Discover Nano, 21, 81. https://doi.org/10.1186/s11671-026-04509-6
17. Ahmed, R., Manik, K. H., Islam, M. S., Rhine, A., Mim, J. J., & Hossain, N. (2026). Green synthesis methods for nanoparticles: Principles, biological routes, and physicochemical approaches toward sustainable nanotechnology. Next Materials, 11, 101929. https://doi.org/10.1016/j.nxmate.2026.101929
18. Kumar, A., Tyagi, P. K., Tyagi, S., et al. (2024). Integrating green nanotechnology with sustainable development goals: A pathway to sustainable innovation. Discover Sustainability, 5, 364. https://doi.org/10.1007/s43621-024-00610-x
19. Lakhani, K. G., Hamid, R., & Marviya, G. V. (2025). A review on plant metabolite-mediated nanoparticle synthesis: Sustainable applications in horticultural crops. Frontiers in Nanotechnology, 7, 1545413. https://doi.org/10.3389/fnano.2025.1545413
20. Elumalai, S., Palanisamy, M., Kuril, A., & Dantinapalli, V. (2025). Applications of green chemistry and nanotechnology as a potential solution for sustainability. In Recent Developments and Challenges in Biological Research (Vol. 10). https://doi.org/10.9734/bpi/rdcbr/v10/3857
21. Alsaiari, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Elboughdiri, N., & Tahoon, M. A. (2023). Plant and microbial approaches as green methods for the synthesis of nanomaterials: Synthesis, applications, and future perspectives. Molecules, 28(1), 463. https://doi.org/10.3390/molecules28010463
22. Saif, S., Tahir, A., & Chen, Y. (2016). Green synthesis of iron nanoparticles and their environmental applications and implications. Nanomaterials, 6(11), 209. https://doi.org/10.3390/nano6110209
23. Rasulov, A., Berdimurodov, E., Demir, M., et al. (2026). Fe_3O_4-based magnetic nanomaterials for heavy metal removal: Comprehensive

review (2020–2024). Emergent Materials, 9, 95. https://doi.org/10.1007/s42247-026-01374-y

24. Gour, A., & Jain, N. K. (2019). Advances in green synthesis of nanoparticles. Artificial Cells, Nanomedicine, and Biotechnology, 47(1), 844–851. https://doi.org/10.1080/21691401.2019.1577878
25. Genuino, H., Hui, H., Eric, N., Lisa, S., & Steven, L. S. (2012). A review of green synthesis of nanophase inorganic materials for green chemistry applications. In Handbook of Green Chemistry (Vol. 8, pp. 223–225).
26. Dube, T. M., Kemboi, D., Manicum, A. E., Mokgalaka-Fleischmann, N. S., & Tembu, J. V. (2023). Advances in phytonanotechnology: A plant-mediated green synthesis of metal nanoparticles using Phyllanthus plant extracts and their antimicrobial and anticancer applications. Nanomaterials, 13(19), 2616. https://doi.org/10.3390/nano13192616
27. Villagrán, Z., Anaya-Esparza, L. M., Velázquez-Carriles, C., Silva-Jara, J., Ruvalcaba-Gómez, J., Edward, A., Rodríguez-Lafitte, E., Rodríguez, N., Balderas-León, I., & Esquivias, F. (2024). Plant-based extracts as reducing, capping, and stabilizing agents for the green synthesis of inorganic nanoparticles. Resources, 13(6), 70. https://doi.org/10.3390/resources13060070
28. Hlatshwayo, S., Thembane, N., Krishna, S. B. N., Gqaleni, N., & Ngcobo, M. (2025). Extraction and processing of bioactive phytoconstituents from widely used South African medicinal plants for the preparation of effective traditional herbal medicine products: A narrative review. Plants, 14(2), 206. https://doi.org/10.3390/plants14020206
29. Herlekar, M., Barve, S., & Kumar, R. (2014). Plant-mediated green synthesis of iron nanoparticles. Journal of Nanoparticles. https://doi.org/10.1155/2014/140614
30. Christian, F., von der Kammer, M., Baalousha, M., & Hofmann, T. (2008). Nanoparticles: Structure, properties, preparation and behaviour in environmental media. In Ecotoxicology of Nanoparticles in the Environment (pp. 45–80).
31. Salim, S., Hari, N., Sudhi, S., & Nair, A. J. (2025). Green synthesis, characterisation and bioactivity of iron oxide nanoparticles using Myristica fragrans leaf extract. The Microbe, 8, 100481. https://doi.org/10.1016/j.microb.2025.100481
32. Soomro, R., Abdelmonem, M., Meli, A. D., et al. (2025). A novel plant-based approach for synthesis of iron oxide nanoparticles and cancer therapy. Discover Chemistry, 2, 25. https://doi.org/10.1007/s44371-025-00091-5
33. Zuhrotun, A., Oktaviani, D. J., & Hasanah, A. N. (2023). Biosynthesis of gold and silver nanoparticles using phytochemical compounds. Molecules, 28(7), 3240. https://doi.org/10.3390/molecules28073240
34. Edo, G. I., Mafe, A. N., Ali, A. B. M., Akpoghelie, P. O., Yousif, E., Isoje, E. F., Igbuku, U. A., Zainulabdeen, K., Owheruo, J. O., Essaghah, A. E. A., Umar, H., Ahmed, D. S., Alamiery, A. A., & others. (2025). Eco-friendly nanoparticle phytosynthesis via plant extracts: Mechanistic insights, recent advances, and multifaceted uses. Nano TransMed, 4, 100080. https://doi.org/10.1016/j.ntm.2025.100080
35. Liu, Y., Wang, S., Wang, Q., Wang, L., Dong, J., & Zhang, B. (2024). Increasing the particle size and magnetic property of iron oxide

nanoparticles through a segregated nucleation and growth process. Nanomaterials, 14(10), 827. https://doi.org/10.3390/nano14100827

36. Zhou, F., Peterson, T., Fan, Z., & Wang, S. (2023). The commonly used stabilizers for phytochemical-based nanoparticles: Stabilization effects, mechanisms, and applications. Nutrients, 15(18), 3881. https://doi.org/10.3390/nu15183881
37. Shafie, A., David, S., Mumin, N., Lim, Y. C., Chellian, J., & Rajabalaya, R. (2025). Green synthesis of silver nanoparticles using plant extracts: Recent advances in mechanisms, parameters, and characterization methods. Current Drug Therapy, 21. https://doi.org/10.2174/0115748855414247251012171623
38. Ebrahiminezhad, A., Zare-Hoseinabadi, A., Sarmah, A. K., Taghizadeh, S., Ghasemi, Y., & Berenjian, A. (2018). Plant-mediated synthesis and applications of iron nanoparticles. Molecular Biotechnology, 60(2), 154–168. https://doi.org/10.1007/s12033-017-0053-4
39. Ahmed, S., Inayat, S., & Javed, I. (2025). Synthesis methods and characterization of iron oxide nanoparticles: A biomedical perspective. Synthesis and Sintering, 5, 109–128. https://doi.org/10.53063/synsint.2025.52284
40. Abbas, J., Jabeen, A., Ajmal, A., et al. (2026). Biogenic synthesis and characterization of antimicrobial, anti-inflammatory, antioxidant, and biocompatible iron oxide nanoparticles (FeONPs) using Arthrospira sp. extract. Discover Nano, 21, 40. https://doi.org/10.1186/s11671-026-04457-1
41. Pasieczna-Patkowska, S., Cichy, M., & Flieger, J. (2025). Application of Fourier transform infrared (FTIR) spectroscopy in characterization of green synthesized nanoparticles. Molecules, 30(3), 684. https://doi.org/10.3390/molecules30030684
42. Mardani, M., Fartushna, I., Khvan, A., Cheverikin, V., Ivanov, D., Kondratiev, A., & Dinsdale, A. (2018). Phase equilibria in the Fe–Ce–C system at 1100 °C. Journal of Alloys and Compounds, 730, 352–359. https://doi.org/10.1016/j.jallcom.2017.09.266
43. Hodoroaba, V.-D., Rades, S., Ortel, E., Mielke, J., Salge, T., & Schmidt, R. (2016). Characterisation of nanoparticles by means of high-resolution SEM/EDS. IOP Conference Series: Materials Science and Engineering, 109, 012006. https://doi.org/10.1088/1757-899X/109/1/012006
44. Akhatova, F., Konnova, S., Kryuchkova, M., Batasheva, S., Mazurova, K., Vikulina, A., Volodkin, D., & Rozhina, E. (2023). Comparative characterization of iron and silver nanoparticles: Extract-stabilized and classical synthesis methods. International Journal of Molecular Sciences, 24(11), 9274. https://doi.org/10.3390/ijms24119274
45. Ashizawa, K. (2019). Nanosize particle analysis by dynamic light scattering (DLS). Yakugaku Zasshi, 139(2), 237–248. https://doi.org/10.1248/yakushi.18-00171-1
46. Kiwumulo, H. F., Muwonge, H., Ibingira, C., et al. (2022). Green synthesis and characterization of iron-oxide nanoparticles using Moringa oleifera: A potential protocol for use in low- and middle-income countries. BMC Research Notes, 15, 149. https://doi.org/10.1186/s13104-022-06039-7
47. Goldstein, J., Newbury, D. E., Joy, D. C., Lyman, C. E., Echlin, P., Lifshin, E., Sawyer, L., & Michael, J. R. (2003). Scanning electron microscopy and X-ray microanalysis (3rd ed.). Springer.

48. Rodríguez-Loya, J., Lerma, M., & Gardea-Torresdey, J. L. (2024). Dynamic light scattering and its application to control nanoparticle aggregation in colloidal systems: A review. Micromachines, 15(1), 24. https://doi.org/10.3390/mi15010024
49. Ntolia, A., Chatzigiannakou, T., Michailidis, N., & Aggeli, A. (2025). A comprehensive physicochemical characterization of silver nanoparticles as a prerequisite for their successful biomedical applications. Inorganics, 13(10), 341. https://doi.org/10.3390/inorganics13100341
50. Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., & Kumar, P. (2018). Green synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. Journal of Nanobiotechnology, 16(1), 84. https://doi.org/10.1186/s12951-018-0408-4
51. Mohamed, H. I., Ullah, I., Toor, M. D., Tanveer, N. A., Din, M. M. U., Basit, A., Sultan, Y., Muhammad, M., & Rehman, M. U. (2025). Heavy metal toxicity in plants: Understanding mechanisms and developing coping strategies for remediation: A review. Bioresources and Bioprocessing, 12(1), 95. https://doi.org/10.1186/s40643-025-00930-4
52. Jara, Y. S., Mekiso, T. T., & Washe, A. P. (2024). Highly efficient catalytic degradation of organic dyes using iron nanoparticles synthesized with Vernonia amygdalina leaf extract. Scientific Reports, 14(1), 6997. https://doi.org/10.1038/s41598-024-57554-5
53. Nkosi, N., Basson, A., Ntombela, Z., Dlamini, N., & Pullabhotla, R. (2024). Green synthesis and characterization of iron nanoparticles synthesized from bioflocculant for wastewater treatment: A review. Biotechnology Notes, 6. https://doi.org/10.1016/j.biotno.2024.12.001
54. Galdames, A., Ruiz-Rubio, L., Orueta, M., Sánchez-Arzalluz, M., & Vilas, J. L. (2020). Zero-valent iron nanoparticles for soil and groundwater remediation. International Journal of Environmental Research and Public Health, 17(16), 5817. https://doi.org/10.3390/ijerph17165817
55. Cardoso, I., Cardoso, R., & Silva, J. (2021). Advanced oxidation processes coupled with nanomaterials for water treatment. Nanomaterials, 11(8), 2045. https://doi.org/10.3390/nano11082045
56. Wang, L., Hu, C., & Shao, L. (2017). The antimicrobial activity of nanoparticles: Present situation and prospects for the future. International Journal of Nanomedicine, 12, 1227–1249. https://doi.org/10.2147/IJN.S121956

Table References:

T1. Ulker, O., Korkmaz, F., Korkmaz, E., & Savaskoparal, A. (2016). Green synthesis of iron nanoparticles using Camellia sinensis extract. International Journal of Green and Herbal Chemistry, 5, 29–37.
T2. Herlekar, M., Barve, S., & Kumar, R. (2014). Plant-mediated green synthesis of iron nanoparticles. Journal of Nanoparticles. https://doi.org/10.1155/2014/140614
T3. Huang, L., Weng, X., Chen, Z., Megharaj, M., & Naidu, R. (2014). Synthesis of iron-based nanoparticles using oolong tea extract for the degradation of malachite green. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 117, 801–804. https://doi.org/10.1016/j.saa.2013.09.054