A Comprehensive Review on Green Synthesis of Iron oxide Nanoparticles from*Ricinus Communis* and their Biotechnological Applications

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Abstract

Nanotechnology has emerged as a rapidly advancing field with significant applications in medicine, agriculture, and environmental science. Among various nanomaterials, iron oxide nanoparticles (IONPs) have gained considerable attention due to their unique magnetic, physicochemical, and biocompatible properties. This review provides a comprehensive review of nanoparticles, with a particular focus on IONPs, including their classification, structural characteristics, and methods of synthesis. Conventional synthesis approaches such as coprecipitation, hydrothermal, sol–gel, microemulsion, and electrochemical methods are discussed along with the green synthesis approach. Special emphasis is given to green synthesis of IONPs using *Ricinus communis*, highlighting its phytochemical composition and role as a reducing and stabilizing agent. Furthermore, the review explores the pharmacological activities associated with *Ricinus communis*, including antioxidant, antimicrobial, antidiabetic, and anti-inflammatory properties, and their relevance in nanoparticle synthesis and biomedical applications. Despite the promising potential of IONPs; challenges such as toxicity, particle size control, and large-scale production remain. This review provide insights into current advancements and future perspectives in the development of eco-friendly and efficient IONPS for biomedical and industrial applications.

Keywords: Iron oxide nanoparticles, IONPs, *Ricinus Communis*, green synthesis of nanoparticles.

1. Introduction

Nanotechnology based researches have gained significant attention in the past few decade leading to the pinnacle of man's insatiable desire for knowledge with its useful applications. ‘Nanotechnology’ is referred to the technology that operates at the nanoscale and has practical applications, such as using individual atoms and molecules to create useful structures (Moriarty et al.,2022). In other words, nanotechnology is "atomically precise technology" or "engineering with atomic precision.” (Sharma et al., 2022).The initial definition of nanoparticle refers to the "nanoscale" with particle size ranging 1–100 nm. The development and use of chemical, physical and biological systems with structural characteristics ranging from single atoms or molecules to submicron dimensions, as well as the integration of the resulting nanostructures into larger systems, are all included in the field of nanotechnology (Nasrollahzadeh et al.,2019). Nanotechnology is associated with systems and materials whose constituent parts and structures, due to their nanoscale dimension, reflect new, much enhanced chemical, physical, and biological qualities, processes, and phenomena. (Patel et al., 2021).

The careful and controlled manipulation, precision placement, modeling, measurement, and production of materials at the nanoscale in order to make matters, systems, and devices by fundamentally novel properties and functions is an alternative meaning from the same lexicon (Zahirifar et al., 2023, Khan et al.,2022). The fact that the chemical, physical, and biological properties of materials at the nanoscale may change significantly from those within a bulk substance exemplifies the essence and promise of nanoscience and nanotechnology. The characteristics of a material may drastically change when its dimensions are decreased below 100 nm (Binns et al., 2022). These macromolecules and particles, which range in size from 1 to 50 nm and are composed of a few molecules, have unique physicochemical characteristics (Van Assenbergh et al., 2018). When utilized in comparable applications, nanoparticles (NPs) have higher performance characteristics than bulk materials. A NP is defined as a collection of atoms linked together with an average radius between 1 and 100 nm, meaning that it usually consists of 10–105 atoms. (Altammar et al., 2023). Significant progress is being made in areas that support the production of NPs and a thorough comprehension of their nature (particle size, content, and structure) and role as catalysts for enhanced chemical reaction performance. A catalyst's performance is largely dependent on the size and distribution of its particles. Because of their enormous surface-to-volume ratio, surface shape, and electrical properties—all of which are correlated with particle size—NPs have benefits as catalysts ((Ndolomingo et al., 2020).

New opportunities for the development of creative nanostructured materials and nanosystems are presented by the discovery of new materials, phenomena, and processes at the nanoscale as well as the development of innovative theoretical and experimental research methods. In terms of its applications in agriculture, electronics, medicine, energy, and other fields, there are numerous present and anticipated developments in nanoscale science and nanotechnology. The pace of these advancements is accelerating (Sivakuma et al., 2013). Nanotechnology can significantly contribute to the expansion of creative techniques used to produce new goods, replace current production machinery, reformulate novel materials and chemicals for better performance that results in lower material and energy consumption, lessen environmental damage, and also aid in environmental remediation (Malik et al., 2023).

While reducing matter and energy use is good for the environment, nanotechnology offers an exciting opportunity to address issues in a more sustainable way. Applications of nanotechnology in the environment include the creation of remedies for existing environmental issues, activities to deal with issues arising from material and energy interactions with the environment, and potential hazards related to nanotechnology (Khan et al., 2019).

1.1 Nanoparticles

Nanostructures with a maximum size of 100 nanometers applied in all directions (x, y, and z) are known as nanoparticles (NPs). Due to their small size and adaptable surface molecule functionalities, these particles are special. Because of this, their vast surface areas and small particle sizes change their molecular interactions, opening up new application areas (Najahi-Missaoui et al., 2020).

The main factors influencing the functioning, activity, and usefulness of NPs are the properties of the particles and their structures. The size and shape of NP can affect its optical characteristics, potential for alteration, and ability to enter cells—all of which are crucial for applications such as imaging studies and cancer treatment (Siddique et al., 2020). The surface charge of a NP is a significant aspect that affects the interaction with the environment, influencing not only cellular contact but also the material's properties and potential for toxicity (Augustine et al., 2020, Stark et al., 2015) viz. food items, medication administration, antibacterial activity, imaging, medicine, and so on (Harish et al., 2022). The effectiveness and activity of the particle can be greatly altered by the NPs' size, shape, and production techniques. Taking into account all of these variables, the material used also plays a major impact in determining the type and function of NP.

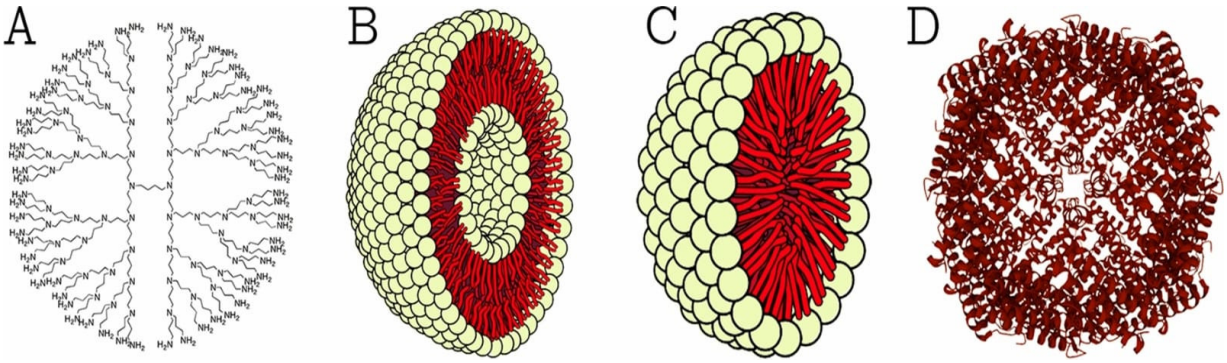


Fig. 1 Types of organic NPs. (A) Dendrimers (B) Liposomes (C) Micelles (D) Ferritin
"Reproduced from Joudeh et al., 2022''

1.2 Classification of Nanoparticles

Due to their unique properties, size, and shape, NPs are categorized into three primary types based on the material: inorganic, carbon-based, and organic. They are further separated into many varieties such as metallic, ceramic, polymeric, and lipid-based (Altammar et al., 2023, (Machado et al., 2015).

1.2.1 Organic Nanoparticles

NPs composed of proteins, carbohydrates, lipids, polymers, or any other organic substance belongs organic nanoparticles (Bhardwaj et al., 2023). Dendrimers, liposomes, micelles, and protein complexes like ferritin (shown in Fig. 1) are well-known organic NPs (Gardikis et al., 2012). Usually non-toxic and biodegradable, these NPs occasionally have a hollow core, as in the case of liposomes. Thermal and electromagnetic radiation, including heat and light, can affect organic nanoparticles (Bhatia et al., 2016). Additionally, they are frequently created via non-covalent intermolecular interactions, which increase their labile nature and provides a pathway for the body to eliminate them (Raut et al., 2024). The possible field of application for organic nanoparticles is determined by a number of factors, including composition, surface shape, stability, carrying capacity, etc. These days, the biomedical industry mostly uses organic NPs for targeted drug delivery and cancer therapy (Bhatia et al., 2016).

1.2.2 Carbon-based Nanoparticles

Carbon based NPs are made solely from carbon atoms. C60 Fullerenes, carbon black nanoparticles, and carbon quantum dots (shown in Fig.2) are well-known examples (Georgakilas et al., 2015). Carbon molecules with a symmetrical closed-cage structure are known as fullerenes. 60

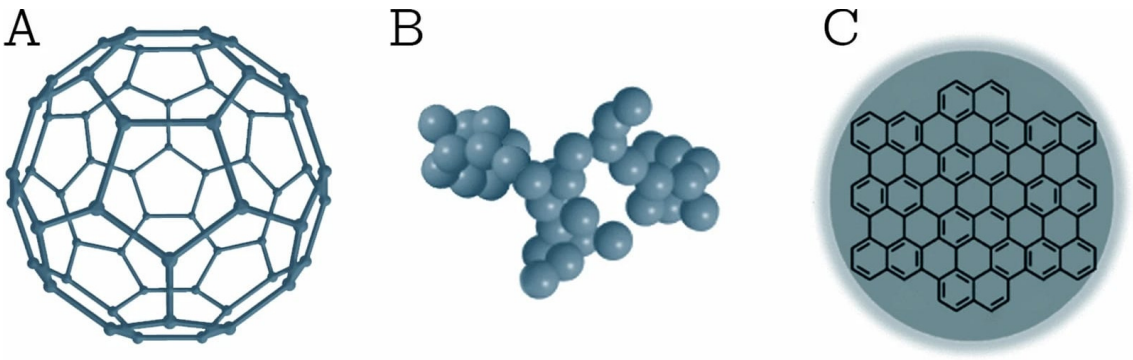


Fig 2. Different types of carbon-based NPs. (A) C60 fullerene (B) Carbon black NPs (C) Carbon quantum dots
"Reproduced from Joudeh et al., 2022''

carbon atoms grouped in the shape of a soccer ball make up C60 fullerenes (Tripathy et al., 2024). Carbon black nanoparticles are collections of highly fused spherical particles that resemble grapes (Elmaghraby et al., 2024). Discrete, quasi-spherical carbon nanoparticles (NPs) less than 10 nm make up carbon quantum dots (Alzahrani et al., 2023).

The unique characteristics of sp2-hybridized carbon bonds are combined with the peculiar physicochemical characteristics at the nanoscale in carbon-based NPs. Due to their distinctive optical, thermal, sorption, electron affinity, electrical conductivity, and strength (Thakur et al., 2018). Drug delivery, bioimaging, photovoltaic devices, and environmental sensing applications to track microbial ecology or identify microbial diseases are just a few of the many uses for carbon-based nanoparticles (Dutta et al., 2022).

1.2.3 Inorganic Nanoparticles

NPs that are not composed of carbon or organic elements are all inorganic viz. metal, ceramic, and semiconductor NPs are common examples. Metal NPs can be monometallic or bimetallic, polymetallic and they are entirely composed of metal precursors (Wan et al., 2023). Alloys or distinct layers (core–shell) can be used to create bimetallic nanoparticles (Wu et al., 2020). These NPs have special optical and electrical features because of the localized surface plasmon resonance characteristics (Khurana et al., 2021). Furthermore, several metal nanoparticles have special biological, magnetic, and thermal characteristics (Rezaei et al., 2024). Due to this, they are becoming more and more crucial components for the creation of nanodevices that have a wide range of physical, chemical, biological, biomedical, and pharmacological uses (Harun-Ur-Rashid et al., 2023). These days, producing cutting-edge materials depends on the size-, shape-, and facet-controlled synthesis of metal nanoparticles (Nguyen et al., 2023).

Semiconductor materials have characteristics properties in between metals and non-metals, are used to create semiconductor nanoparticles. Compared to bulk semiconductor materials, these NPs have distinctively large bandgaps and exhibit notable property changes with bandgap tuning (Mishra et al., 2023). These inorganic NPs are hence crucial components of optical, electrical, and photocatalysis devices (Merupo et al., 2023). Carbonates, carbides, phosphates, and oxides of metals and metalloids, including calcium and titanium, make up ceramic nanoparticles (NPs), which are inorganic solids (C Thomas et al., 2015). They can be found in amorphous, polycrystalline, dense, porous, or hollow forms and are often created by heat and subsequent cooling (Wang et al., 2016). Due to their great stability and high load capacity, they are mostly utilized in biomedical applications. However, they are also employed in other fields as photonics, optoelectronics, dye degradation, and catalysis (Huang et al., 2021).

2. Iron Oxide Nannoparticles

Iron oxides (compounds) are created when iron and oxygen react chemically; there are about 16 known iron oxides. Iron (III) oxide can be found in nature as rust (Usman et al., 2018). Iron oxides are generally common, extensively utilized due to their low cost, and essential to numerous biological and geological processes. Magnetite (Fe3O4), maghemite (γ-Fe2O3), and hematite (α-Fe2O3) are the three most prevalent types of iron oxides found in nature. This review focuses on these oxides since they are crucial to scientific technology (Kumar et al., 2021). Superparamagnetism is a special kind of magnetism seen in ferromagnetic nanoparticles (NPs) smaller than 10–20 nm. Ferromagnetic materials include oxides, alloys, elemental metals, and other chemical compounds that are magnetized by an external magnetic field. This is an important phenomenon that usually only occurs in NP systems (Mohamed et al., 2019).

Magnetic iron oxide (Fe3O4 and γ-Fe2O3) NPs haveinteresting in biomedical applications for protein immobilization, such as diagnostic magnetic resonance imaging (MRI), thermal therapy, and drug delivery, due to their low toxicity, superparamagnetic characteristics, such as surface area and volume ratio, and straightforward separation methodology (Hasany et al., 2012). Although iron's reactivity is a major issue at the nanoscale, it is significant in macroscopic applications, especially rusting (Bae et al., 2018). The extreme reactivity of iron makes it difficult to study and inconvenient for many applications (Chaudhari et al., 2024). However, iron's potential has gained attention due to its strong magnetic and catalytic qualities (Pereira et al., 2012).

By self-heating, applying an external magnetic field, and traveling along the field of attraction, iron oxide nanoparticles can be quickly and readily brought into magnetic resonance. These behaviors are significantly influenced by the synthetic processes, crystallization, size, shape, and quality of the iron oxide nanoparticles (Zhang et al., 2024).

2.1Magnetite

Magnetite, the most prevalent and significant iron oxide, has an equal stoichiometric distribution of Fe^{2+} and Fe^{3+}, however this ratio is frequently unstable and produces a layer that is low in Fe^{3+}. An inverse spinel structure and a face-centered cubic unit cell with an edge length of 8.396 Å are its structural characteristics. Each unit cell is made up of 8 Fe^{2+}, 16 Fe^{3+}, and 32 O_2atoms (Santos Carballal et al., 2015). When comparing the inverse spinel structure of a mineral with the general formula (A2+B23+O42−) to Fe_3O_4 (magnetite), it is found that half of the Fe_{3+} and Fe_{2+} ions occupy the tetrahedral sites, while the other half of the Fe_{3+} ions occupy the octahedral sites. When the iron atom's d-orbitals degenerate in the presence of a ligand, the divalent Fe ions occupy the octahedral positions because they acquire greater crystal field stabilization energy. The other crystal forms of magnetite include octahedron and rhombodecahedron (Magasi et al., 2023).

Surfactants can be used to modulate the degree of agglomeration that magnetite nanoparticles tend to generate. Tipsavat et al. used the solvothermal approach to produce magnetite nanoparticles and investigated the impact of poly(vinyl)pyrrolidone (PVP) as a surfactant at varying concentrations on the magnetite nanoparticles' electrochemical performance (Tipsawa et al., 2018).

2.2 Hematite

Hematite (α-Fe_2O_3), the second most important iron oxide, is thought to be the most stable under ambient circumstances due to its thermodynamic stability. It should be mentioned that corundum(α-Al2O3) and hematite are isostructural. With lattice constants of a = 5.0346 Å and c = 13.752 Å, hematite is made up of Fe^{3+} ions packed densely in octahedral coordination with oxygen atoms in hexagonal closed packing (Voloshina et al.,2017). Fe^{3+} ion sheets are placed between two densely packed oxygen layers that are joined by covalent bonds to form the structure. Furthermore, a face, three edges, and six vertices connect the three-dimensional framework of hematite's crystal structure to its thirteen neighbors. As hematite contains Fe in a trivalent state, two of the three possible oxygen octahedrons are occupied and each oxygen atom is coupled to two Fe ions. Because of this configuration, hematite is neutral and has neither an excess nor a deficiency of charge (Wan et al., 2023).

A few factors, including the particle's size and shape, structure, crystallinity, morphology, cation substitution capacity, and the induction of dipole-dipole and exchange interactions, have a significant impact on the magnetic behavior of hematite nanoparticles. Tadic et al., 2019 conducted an interesting study that took into account the shape of the nanoparticles and calculated the magnetic characteristics of hematite using three primary shape-related parameters: its circularity, elongation, and convexity.

2.3 Maghemite

After hematite, maghemite is the second most stable polymorph of iron oxide. It shares isomorphous crystal structures with magnetite (edge length, a = 8.346 Å) because it is an allotropic version of magnetite (Coduri et al., 2020). Since every Fe atom in the crystal is in its Fe^{3+} state, it is also the fully oxidized polymorph of iron oxide. Because the unit cell has two and one-third cation vacancies, its spinel crystal structure preserves the unit cell's charge neutrality. The crystal structure in which maghemite would exist is likewise determined by the distribution of these vacancies. Maghemite has an inverted spinel structure if the vacancies are dispersed randomly, which is the compound's usual condition (Coey et al., 2021). Maghemite can occur in an ordered structure with partially ordered voids, aside from the randomly distributed crystal structure. Furthermore, it can exist in a tetragonal structure with fully ordered vacancies and a threefold doubling (Shokrollahi et al., 2017).

In contrast to hematite's anti-ferromagnetism, this polymorph displays ferrimagnetism. As previously mentioned, it is challenging to distinguish between magnetite and maghemite unless sensitive characterization methods are used. The direction of orientation with respect to the magnetic field, where the former aligns parallel and the latter aligns anti-parallel, can be used to identify the A site and B site hyperfine fields from the Mossbauer spectrum of maghemite using large applied magnetic fields. Because ferric ions at the A and B sites have identical Mossbauer parameters, the magnetic splitting of A is seen to grow while that of B is suppressed. This resolves the issue of not being able to discern the components of the spectrum (Kuhn et al., 2002).

3. Conventional methods for synthesis of IONPs (FeONPs)

The manufacture of iron oxide nanoparticles is still difficult since the desired characteristics of these particles greatly depend on the experimental method used. This is due to the fact that one of the key characteristics must be "traded off" with any other attribute, such as the particle size, oxidation state, stoichiometry, or magnetic property. Furthermore, it is challenging to produce small

nanoparticles with a higher saturation magnetization coefficient since these nanoparticles are intrinsically colloidal (Ramimoghadam et al., 2014).

3.1 Conventional methods

3.1.1 Coprecipitation

The most common approach for creating magnetic IONPs is wet chemical coprecipitation, which is more efficient than other production techniques. The process is straightforward and involves the precipitation of the magnetite, maghemite, and ferrous hydroxide polymorphs of iron oxides through the reaction of an aqueous solution of ferrous and ferric salts in the presence of an alkali given sufficient incubation time. By adjusting the pH of the solution, the synthesis process can be modified to produce the various phases of iron oxide. Magnetite is produced using a basic precursor (between 8 and 14) and a 2:1 Fe^{2+}/Fe^{3+} ratio (Ramimoghadam et al., 2014). Magnetite is easily oxidized to maghemite because it is extremely sensitive to oxygen. Therefore, non-oxidizing circumstances are ideal for magnetite formation. Magnetite oxidation is caused by iron ions desorbing from the magnetite surface and creating cationic vacancies to balance the structure's charge, which results in the creation of maghemite.

3.1.2 Hydrothermal Synthesis

Autoclaves that are kept at high temperatures and pressures are used in hydrothermal synthesis. The aqueous iron precursor solutions undergo two steps of ferrites formation in a closed chamber, ideally an autoclave: hydrolysis and mixed metal hydroxide oxidation. Magnetite generation is still the most "profitable" process, even if it can be used for other phases of iron. Larger magnetite sizes were produced when the reaction's water content was increased, indicating that the solvent now controls the particle size. Like the coprecipitation approach, the nucleation and growth rate have an impact on and define the particle size of the nanoparticles produced using this process. It is well known that, even if the reaction time is prolonged, the resulting nanoparticles will exhibit a decrease in size during the growth phase if the nucleation phase is shorter than the growth phase at higher temperatures (Ramimoghadam et al., 2014; Sodipo et al., 2016).

3.1.3 Sol-Gel Synthesis

The sol-gel method is a two-step procedure that starts with the precursor's hydroxylation in a liquid state and ends with its condensation, which produces a sol of nanoparticles. The prolonged condensation and inorganic polymerization processes would result in the wet gel, a three-dimensional metal oxide network. The final crystalline state can be obtained by additional heat

treatments. The structure and characteristics of the gel are accounted for by reaction circumstances, which affect their reaction kinetics and development. These conditions include temperature, solvent, pH, agitation, and the type of precursors used. By immediately heating the gels at 673 K, maghemite nanoparticles in the size range of 6–15 nm have been readily produced (Parashar et al., 2020). Custom-made nanoparticles with a predetermined structure can be created using this method, which also has the advantage of producing pure amorphous phases, controlling particle size and solution monodispersity, regulating microstructure and the homogeneity of reaction products, and requiring relatively low processing temperatures. IONPs have been widely implanted into appropriate matrices using the sol-gel process to serve as multifunctional materials in a variety of applications (Ramimoghadam et al., 2014; Sodipo et al., 2016; Laurent et al, 2010).

3.1.4 Microemulsion Synthesis

Transparent solutions known as microemulsions are created when an immiscible phase, which is present as tiny droplets, is distributed throughout a continuous phase. It should be mentioned that the immiscible phase may be polar or non-polar. These microemulsions might be water-in-oil or oil-in-water systems. Here, the key process is the use of surfactants to lower the total surface energy of the solution system, hence reducing the surface tension between the two phases and maintaining the stability of the droplets. This causes micelles to form, which in turn causes the resulting iron oxide nanoparticles to disperse. The main benefit of this technique is the ease of fabrication of a variety of self-assembled structures, including spherical, lamellar, cylindrical, and bio-continuous microemulsions.

3.1.5 Sonochemical Synthesis

Due to the extremely fast rate of cooling used in the process, the sonochemical approach uses ultrasound to create new phases of the material and highly monodisperse nanoparticles. Because of the hot spot created by the quick collapse of acoustically generated holes, the salt precursors are transformed into nanoparticles at high temperatures. Iron oxide nanoparticles with special qualities are known to be produced using this technique (Ramimoghadam et al., 2014).

3.1.6 Electrochemical Synthesis

The electrochemical method is a relatively new production technology for IONPs, specifically the magnetite and maghemite polymorphs. With the exception of the temperature used not exceeding the electrolyte's boiling point, this approach is the most straightforward of all the ones outlined and

offers control over the particle size because extreme reactive conditions are not required. Kinetic and thermodynamic control over the synthesis can be created because the electrochemical method's adjustable parameters are the current and potential. The experiments are simple, but because the reactions occur at room temperature, the necessary nucleation sites and growth are not reached, resulting in amorphous products or randomly arranged nanoparticles (Ramimoghadam et al., 2014; Zeng et al., 2017).

4. Green Synthesis of IONPs (FeO NPs)

Green synthesis is anecologically friendly and less harmful method than those made using any of the aforementioned methods; this synthesis approach has attracted a lot of interest from material scientists for the synthesis of IONPs. Numerous biological sources, including plants, fungi, viruses and algae have been widely employed to create a variety of iron oxide nanoparticles. Biomaterials function as reducing, capping, and stabilizing agents, these particles are typically seen to be more stable in this aspect. The two primary steps in any type of green synthesis are bioreduction and biosorption. In the former, metal ions are chemically reduced to their stable forms, and in the latter, they bind to the surfaces of living things to form stable complexes.(Devi et al., 2019; Chatterjee 2020 et al., 2020; Jubran et al., 2020; Priya et al., 2021; Salem et al., 2019).

Using the one-step green synthesis method, Lakshminarayanan et al. created hematite nanoparticles from *Bauhinia tomentosa* leaf extract, which were then utilized to create 1,3-diolein via enzyme-mediated processes (Lakshminarayanan et al., 2021). IONPs of various sizes and polydispersity were produced using a variety of different plant extracts including seeds, seed coat, flowers, peels, petals, fruits, and leaves from plants such green tea, *Solanum trilobatum*, *Persia americana*, and *Camellia sinsensis*. Plants are the most sought-after source for environmentally friendly nanoparticle production due to the vast variety of extract choices available. Secondly, due to their better tolerance and capacity for bioaccumulation, microorganisms like bacteria and fungus are regarded as sources of synthesis since they secrete significant quantities of extracellular hydrolyzing enzymes, such as reductases to decrease metals. As they can grow in harsh environments and have a quicker doubling time than fungi, bacteria are used more frequently (Priya et al., 2021).

The purpose of this study is to analyze current scientific research on environmentally friendly "green" synthesis techniques for metal and magnetic nanoparticles. "Green" nanoparticles are being utilized extensively as adsorbents, photocatalysts, and antimicrobials (Vrček et al., 2016). Due to their great biocompatibility and low toxicity, "green" magnetic nanoparticles can be used in

biomedical applications, particularly for magnetic hyperthermia, contrast imaging, and targeted drug administration. Scanning electron microscopy, transmission electron microscopy, energy-dispersive analysis, X-ray diffraction analysis, X-ray photoelectron spectroscopy, FTIR spectroscopy, Raman spectroscopy, and magnetic force microscopy can all be used to describe the structure and morphology of synthesized magnetic nanoparticles. Weak magnetic fields can be detected using magnetic force microscopy (MFM), a scatter-sensitive method with a resolution of up to 10 nm. Because MFM may be used in liquid, vacuum, or air and has straightforward sample preparation requirements, it is a universal technique for analyzing magnetic nanoparticles (Passeri et al., 2021).

4.1 *Ricinus communis:* Phytochemical Composition

The Euphorbiaceae family, also known as the spurge family, is a diverse group of plants with many species that exhibit remarkable adaptability in a variety of ecological contexts. This adaptability is reflected in the family's morphological diversity, which ranges from little herbs to massive trees and demonstrates the family's evolutionary flexibility. The Euphorbiaceae family, also known as the spurge family, is one of the largest and most diverse families of flowering plants. It is found throughout the tropics and includes about 300 genera and 8000 species (Chaudhary et al., 2023). The Euphorbiaceae family is well known for its ethno medical uses and for generating bioactive diterpenoids, which have been connected to many species' biological activity (Kemboi et al., 2020).

In certain forest areas, like the Amazon Rainforest and the Congo Basin, the Euphorbiaceae family is known to be the most common (Ruziman et al., 2022). Additional traits of the Euphorbiaceae family that demonstrate to its adaptability and resilience include rich and varied flora, such as Manihot esculenta (cassava) and Jatropha curcas (Barbados nut), which are common in both small-scale mined and unmined areas (Somineni et al., 2025).

4.2Geographical Distribution of *Ricinus communis*

Ricinus communis is mainly native to the Southeast Mediterranean Basin, Eastern Africa and the Indian subcontinent (Chand et al., 2021), but it has been extensively grown and adapted in many other places, including tropical and subtropical climates like China and the Americas, as well as all continents except Antarctica (Salihu et al., 2014). In ancient civilizations, its seeds were prized for its industrial and medicinal properties (Chouhan et al., 2021).The global distribution of *R. communis* exceeded its initial range due to a number of reasons, including human commerce and

unintentional seed dissemination. *R. communis's* historical origins, ecological adaptability and human activity all have an impact on its distribution in South Africa (Salihu et al., 2014).

4.3Phytochemical Properties of *Ricinus communis*

4.3.1 Pharmacological Activity

A wide range of effects of drugs or other medical compounds on biological systems are referred to as pharmacological activities . In addition to potential drawbacks or responses, some activities may have therapeutic benefits like symptom relief, sickness prevention, or improved wellbeing (Golovinskaia et al., 2021). The range of biological effects that these plants' bioactive compounds exhibit is referred to as "pharmacological activities" when addressing medicinal plants (Polito et al., 2019). The pharmacological qualities of *Ricinus communis* are widely recognized and are primarily associated with its seeds. Ricin, a toxic protein, and castor oil, which have long been used for medicinal purposes, are produced from *Ricinus communis* seeds (Franke et al., 2019).

4.3.2Antioxidant Activity

Numerous studies have significantly enhanced the identification of antioxidant activity of *R. communis* (Ihekuna et al., 2019; Ahmed., 2018). Solvent extracts such as methanol, ethanol, ethyl acetate, n-hexane, chloroform, n-butanol and aqueous have been produced and subjected to conventional antioxidant assays in order to assess the antioxidant capacity of *R. communis* roots. Ahmed and Iqbal evaluated the extracts' total phenolic content (TPC) and total flavonoid content (TFC) and examined their capacity to scavenge DPPH radicals. All extracts demonstrated considerable antioxidant activity, according to the results, with ethyl acetate and chloroform exhibiting the maximum DPPH scavenging activity at 41%. With values of 131 mg/mL, 127 mg/mL, and 117 mg/mL gallic acid equivalent, respectively, the TPC analysis also showed significant activity in ethyl acetate, n-butanol and aqueous extracts. Methanol and aqueous extracts showed the maximum activity of TFC at 32 µg/mL each, while the control showed 38 µg/mL. These results show that *R. communis* roots are a potent source of antioxidants, suggesting that they may have therapeutic uses. The antioxidant activity of ethanolic extracts from *R. communis* seeds and leaves was examined by Ihekuna et al. in a related investigation. R. communis extracts shown strong antioxidant activity in both in vitro and in vivo tests, with IC50 values of 62.86 ±0.54 and 62.39 ±0.18 µg/mL in nitric oxide radical inhibition assays and 77.17 ±0.36 and 69.33 ±0.26 µg/mL for seed and leaf extracts in DPPH assays, respectively. The liver and kidneys' levels of catalase and superoxide dismutase increased after treatment with these extracts, indicating a

protective effect against oxidative stress. Their results showed that the ethanolic extracts exhibited a significant level of antioxidant activity, indicating the presence of bioactive compounds that may neutralize free radicals and lessen oxidative damage.

4.3.3Antifungal/Antimicrobial Activity

Researches on the antifungal capabilities of *Ricinus communis*, well-known for its varied pharmacological characteristics, have shown that it is effective against a variety of fungal species. Dikhoba et al. looked at the antifungal potential of *R. Communis*, who demonstrated that the plant's leaf extract was efficient against fungi, with *R. communis* leaf extract showing potential antifungal activity with a minimum inhibitory concentration (MIC) ranging from 0.08 to 2.5 mg/mL. Furthermore, *R. communis* had a minimum inhibitory concentration (MIC) of 0.08 mg/mL against *Fusarium verticilloides*, which is similar to the antibiotic Amphoteracin B. Additionally,*R. communis'*s overall effectiveness against *Aspergillus ochraceous* was noteworthy, demonstrating its strength in inhibiting fungal development. The researchers employed conventional microbiological methods to determine the MIC values, or the concentration at which the fungal pathogen's growth is halted. Istaufa et al., also investigated the antibacterial qualities of *R. communis* leaf extracts and fractions against a number of illnesses, including tuberculosis (TB), which is brought on by the bacteria Mycobacterium tuberculosis. With an average colony count decrease from 20.33 at 100 µg/mL to 0 at 200 µg/mL, the ethanolic extract demonstrated the most encouraging results, totally stopping bacterial growth at 200 µg/mL. Other solvents like acetone and methanol also showed inhibitory effects; the methanol extract reduced colonies from 17.33 at 100 µg/mL to 0 at 150 µg/mL and inhibited growth at 100 µg/mL. Colony numbers were decreased by the acetone extracts from 55.66 at 100 µg/mL to 0 at 200 µg/mL. When the minimal inhibitory levels of several extracts were measured, n-hexane shown action at 10,000 µg/mL, ethyl acetate at 40,000 µg/mL and chloroform at 5000 µg/mL. These results imply that *Ricinus communis* L. leaf extracts, which successfully suppress *Mycobacterium* tuberculosis growth at different doses and solvents, have considerable potential as an adjunctive treatment for tuberculosis. The aforementioned studies evaluated the antifungal and antimicrobial characteristics of *R. communis* using a range of solvents, from ethanol and methanol to chloroform and n-hexane, and techniques, such as MIC, MLC and disc diffusion. Each method and solvent selection affected the observed potency (Suurbaar et al., 2017).

4.3.4 Anti-Inflammatory Activity

A recent study has demonstrated the anti-inflammatory properties of *R. communis*, indicating that it may be useful as a treatment for inflammatory conditions. Lee et al. looked into how *R. communis* leaves might successfully activate Nrf2 to lessen the effects of dexamethasone-induced muscle atrophy in order to shed light on their anti-inflammatory qualities. Using both in vitro and in vivo models, the study assessed muscle atrophy and Nrf2 activation, providing mechanistic insights into the anti-inflammatory properties of *R. communis* leaves. The investigation's findings demonstrated that after treatment with the extract at concentrations of 10 µg/mL and 50 µg/mL, the TNFAIP6 gene (tumor necrosis factor-inducible gene 6) was elevated by 2.3 and 3.1 times, respectively. TNFAIP6, also known as TNF-stimulated gene 6 (TSG-6), is essential for exerting anti-inflammatory andprotective effects via decreasing neutrophil infiltration in disease models. By attaching to and interacting with many chemokines, the gene's product contributes to the anti-inflammatory response. These findings imply that *R. communis* leaf extract has the potential to have significant anti-inflammatory effects, which may enhance its therapeutic benefits (Hajrah et al., 2019).

4.3.5 Antiparasitic Activity

Recent research confirms the strong antiparasitic action of *R. communis*, especially its ricinoleic acid and seed oil examined the cysticidal effectiveness of three commercial-grade castor oils against the amoebiasis causing protozoan parasite *Entamoeba histolytica* in vitro. For 10 hours, each oil was applied to cyst cultures at concentrations of 10–100 µg/mL. In a dose-dependent manner, morphological analysis revealed significant membrane breakdown, cytoplasm leaking and cyst wall integrity degradation. The measured EC50 values ranged from 35 to 50 µg/mL, which are within the estimated intestine concentrations with regular oral dosing. The high concentration of ricinoleic acid, which is cytolytic to protozoan membranes through fatty acid-induced micellization and osmotic imbalance, was attributed by the authors to this activity. Additionally, ricinoleic acid and methyl ester anthelmintic activity against *R. communis* seed were isolated and characterized by Berhanu et al. Pure fatty acid derivatives were obtained by petroleum ether extraction, base hydrolysis and esterification. These compounds were then evaluated against *Caenorhabditis elegans* as a nematode model and activity was assessed by worm motility and survivability using light microscopy. More than 97% of the worms were killed by the agents at a dose level of 1 mg/mL in 8 hours and no remaining worms recovered in 24 hours. Ricinoleic acid has substantial binding energies to succinate dehydrogenase (−5.41 kcal/mol) and glucose-6-phosphate

dehydrogenase (−3.76 kcal/mol), two enzymes critical to helminth metabolism, according to a molecular docking research. Additionally, in silico ADME screening demonstrated low toxicity risk, drug-likeness, and excellent oral bioavailability. Ricinoleic acid offers a lot of promise for use as a plant anthelmintic medication, according to the study (Berhanu et al., 2025).

5. Green synthesis of IONPs (FeO) Nanoparticle from *Ricinus Communis* Leaf Extract

Green nanotechnology integrates the use of plant elements to ensure a field with good safeguarding of the safety of life. It is a favorable application in the field of nanotechnology, reducing dangers while improving the environment's resilience (Khan et al, 2019). Extracts from diverse plant parts, including flowers, leaves, seeds, and roots, are used to create metal nanoparticles for a variety of uses (Beyene et al., 2017). Plant extracts, exudates, and inactivated plant tissue are used in biological synthesis (Singh et al., 2021). There are many sources of metabolites with therapeutic qualities, plant-based biogenic production of nanoparticles possesses antibacterial potential (Murugan et al.,2025). Many plants, including *Erodium cicutarium* and Nerium oleander, have been used to create iron nanoparticles. *Ricinus communis*, also known as castor, is a flowering plant that has been used as an antioxidant, fungicide, antiulcer, wound healer, laxative, antiasthmatic, and insecticide agent because it contains alkaloids, flavonoids, steroids, saponins, glycosides, and other compounds (Nand et al., 2025).

This study used *Ricinus communis* (castor) to biologically synthesize iron and silver nanoparticles, which were then analyzed using UV-Vis absorption spectroscopy, Fourier transform infrared (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS), and transmission electron microscopy (TEM) and determination of synthetic nanoparticles' biological significance, MIC and antibacterial tests.

5.1 Collection and identification of plant

Mature, healthy *Ricinus communis* medicinal plant leaves (Fig. 3) aregathered identified and verified the gathered plant.



Fig 3.*Ricinus communis* leaves.

5.2Preparation of *Ricinus communis* leaf extract

The dust of fresh *Ricinus communis* leaves are carefully cleaned with tap water and then distilled water before being allowed to air dry. An aqueous extract is prepared using about 10 g of cleaned leaves were chopped into tiny bits, crushed with a mortar and pestle, and combined with 100 mL of double-distilled water. Methanol and an additional 10 g of leaf extract were combined, and the mixture was incubated for an entire night at 60–70 rpm. After filtering the mixture with Whatman's No. 1 filter paper, it was employed for more research (Linima et al., 2023).

5.3 Precipitation of iron nanoparticles

The aqueous leaf extract was combined in a 1:1 ratio with a 0.1 M $FeCl_3 \cdot 6H_2O$ solution made in double-distilled water. The ferric chloride solution was mixed with an equivalent volume of leaf extract dropwise while being agitated at room temperature using a stirrer. Iron nanoparticle production was indicated by the solution's color changing from pale yellow to black. After being centrifuged at 6000 rpm and cleaned with water, the precipitate solution was dried in an oven at 60°C (Linima et al., 2023).

6. Characterization of the green synthesized IONPs

In order to attain size and morphology) that are equivalent to physical and chemical methods, green synthesis techniques for metallic nanoparticles are constantly being refined and modified. The production of nanoparticles is typically indicated by a change in the color of the reaction mixture; however, this does not ensure their formation, thus further procedures must be

performed to identify the particles created. One of the most often used techniques to verify the formation of nanoparticles is continuous UV spectroscopy of the reaction mixture (Andrade-Zavaleta et al., 2022; Buarki et al., 2022). At the moment, a range of characterization techniques are helpful for assessing the characteristics and applications of produced nanoparticles as well as streamlining synthesis processes (Mourdikoudis et al., 2018). But no single tool is able to describe every property of a substance. Therefore, a variety of complementary and confirmatory methods for characterizing nanoparticles should be used. The most often investigated characteristics of nanoparticles are size, shape, charge, and surface topology are. However, the sample preparation process makes characterizing nanoparticles challenging, and the characterization method chosen depends directly on the necessary attributes.

6.1 UV–VIS Spectroscopy

A popular technique for examining the optical and structural characteristics of nanomaterials, including form, size, agglomeration state, concentration, refractive index, and colloidal stability, is UV–Vis spectroscopy, which is based on the Beer–Lambert law (Nair et al., 2018).

As mentioned earlier, this method can be used to verify that IONPs have formed. Metal nanoparticles with a diameter of less than 100 nm effectively scatter optical light due to the surface plasmon resonance, which is the resonance of the metal's conduction electrons. However, the absorption spectra can shift toward longer wavelengths as the particle size grows. The bandwidth, amplitude, and wavelength peak of the plasmon resonance are influenced by the nanoparticle's composition, surroundings, form, and size (Karpagavinayagam et al., 2019; Niraimathee et al., 2016; Bouafia et al., 2020; Aziz et al., 2020).

6.2 Scanning Electron Microscopy (SEM)

An electron beam, usually between 1 and 30 keV, is used in scanning electron microscopy (SEM), a non-destructive analytical technique for surface and microstructural investigation, to scan the sample's surface (Inkson et al., 2016; Vijayaraghavan et al., 2017). The degree of dispersion, homogeneity, and purity can all be assessed with this method (Patravale et al., 2012). Three types of electrons—backscattered (or primary), secondary, and auger electrons—as well as X-rays are released when the electron beam hits a nanoparticle. Both primary and secondary electrons are employed in SEM, with the latter being used to produce high-resolution images that show details as fine as 1–5 nm (Patravale et al., 2012). The three-dimensional appearance of the surface structure,

one benefit of SEM characterization is that it also aids in studying the surface features of the IONP sample (Kanagasubbulakshmi et al., 2017).

6.3 EDX

One method for assessing the purity and elemental makeup of produced nanoparticles is energy-dispersive X-ray spectroscopy (EDX) (Yadav et al., 2018). EDX is a technique used in conjunction with SEM because, as previously mentioned, when an electron beam strikes a nanoparticle, X-rays are released along with the three types of electrons; the energy of the generated X-rays varies on the material under research. By shifting the electron beam across the material, each element in the sample may be seen, providing an overall mapping of the sample by analyzing elements at and near the surface and calculating their fraction at various places (Titus et al., 2019).

6.4Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is used to examine the kinetics of the nanostructure's chemical and physical processes at the atomic level (Zhang et al., 2020). An objective lens is used to magnify and focus the electrons that are transmitted after an electron beam interacts with the material to generate the image. In contrast to absorption processes that take place in the light microscopic image, diffraction processes are produced when the electron beam interacts with the material in the TEM image. The sample needs to be prepared to withstand both the electron beam and the high-vacuum chamber because it will be subjected to a high vacuum during the analysis (Inkson et al., 2016). TEM images are influenced by the energy of the electrons, the diameter of the objective aperture, the density and thickness of the sample, and the variations in electron densities of the structures. Furthermore, either unscattered electrons (light field image) or deflected electrons (dark field image) can be used to create the contrast image. The morphology of nanostructures, including particle size, aggregation state, electronic state, and chemical composition, are frequently described using this method (Cheng et al., 2021). Additionally, the electron energies for the beam are typically 100 keV for normal images and 1 MeV for high-resolution imaging, depending on the sample (Inkson et al., 2016).

6.5 X-Ray Diffraction (XRD)

A non-destructive method for examining a material's crystallographic structure is X-ray diffraction (XRD). Additionally, it can be utilized to ascertain element proportions, atom locations inside the unit cell, unit cell properties, and atom counts within the unit cell (Fouladi-Fard et al., 2022). A portion of the beam is transmitted when the X-ray beam interacts with the atomic planes;

the remaining portion is absorbed, refracted, dispersed, and diffracted by the sample. One of the most popular methods for determining crystalline perfection and defect studies in single crystals, as well as detailed studies of structure and phase transformation in materials, is high-resolution powder X-ray diffraction (HRXRD), which can be used to obtain finer information about the structure of nanoparticles, such as ion spacing and bond length of related substances in single crystal cells (Malinov et al., 2019). By measuring the diffraction angle that results from an X-ray beam striking the nanoparticles, the lattice and structural properties can be ascertained.

6.6 Zeta Potential (ζ)

Unlike the other parameters mentioned above, the zeta potential cannot be measured directly. Therefore, all of the equipment used to determine its value measures other parameters, like the colloid vibration current and electrophoretic mobility, and then uses those measurements to calculate the zeta potential. Zeta potential is frequently measured using electrophoretic and electroacoustic techniques (Dukhin et al., 2020). Electrophoresis, which relies on the motion of particles in an electric field, is the foundation of the first technique. Due to the electrical charges on their surface, the nanoparticles interact with the field, causing this movement. The direction and speed of the movement are determined by the electric field, the nanoparticles' surface charge, and the suspension medium (Titus et al., 2019).

The velocity of the nanoparticles is measured using electrophoretic light scattering (ELS) via a laser Doppler setup. This allows the velocity and direction of the moving particles to be determined inside the frame of reference of the measuring cell (Dukhin et al., 2020). Conversely, electroacoustics techniques can be defined as the high-frequency study of electrokinetics. When ultrasound waves travel into a fluid medium that contains ions, the interplay between the acoustic and electric fields causes it (Dukhin et al., 2010). Colloid vibration potential (CVP) or colloid vibration current (CVI) and electrokinetic sonic amplitude (ESA) are the two forms of electroacoustic processes based on the driving force that causes particle movement in one direction relative to the liquid (Mohammadi-Jam et al., 2022). In CVP, charged colloidal particles moving in relation to the liquid under the effect of an ultrasonic wave produce an AC electric current (Dukhin et al., 2020). The opposite effect occurs when ESA vibrates the nanoparticles in the liquid using an AC electric field. Each particle's oscillation creates tiny acoustic dipoles that, depending on the applied frequency, create an ultrasonic wave that may be detected by a transducer (Greenwood et al., 2003; O’brien et al., 1995).

7. Antimicrobial Properties of Green SynthesizedIONPs

The hunt for new compounds with antibacterial potential is especially important given the rise of antibiotic-resistant strains as the biggest global danger to public health. As bactericidal or antibacterial agents, free iron ions and other metal and metal oxide nanoparticles (NPs) such as silver, ZnO, Al_2O_3, and TiO_2 have been tested (Slavin et al., 2017; Majeed et al., 2016). However, the primary issue with employing antibacterial nanoparticles is their high toxicity, which has been documented for ZnO (Wang et al., 2018); therefore, a nanoparticle that is both biocompatible and biologically active against bacteria is required (Alghuthaymi et 2015; Zakariya et al., 2022). Because of their bactericidal qualities and in vitro and in vivo biocompatibility, IONPs have lately become a viable substitute in this situation. Although nanoparticles have the potential to be antibacterial agents, there have been some documented dangers to the environment and human health. On the other hand, IONPs have been demonstrated to be safe and non-toxic in mammalian cell culture, which is a highly sought-after property for usage in pharmacological, therapeutic, and biological applications. Fe_2O_3, magnetite Fe_3O_4, and limonite $Fe_2O_3 \cdot H_2O$ are the most pertinent IONPs with biological activity (AlMatar et al., 2018; Ebrahiminezhad et al., 2018).

7.1 Mechanism of Antibacterial activity of IONPs

A number of mechanismsinvolving the interaction between the nanoparticles and bacterial cells account for the antibacterial activity of the nanoparticles (Padmavathy et al., 2008).

The unique characteristics of the nanoparticles and the relevant bacterial strains may determine the precise mode of action. Because of their tiny size, nanoparticles (NPs) attach to the bacterial surface and then enter the bacterial cell (Jabbar et al., 2023). By creating holes in the bacterial membrane, silver nanoparticles (AgNPs) can weaken its integrity. AgNPs can also interact with intracellular proteins to produce reactive oxygen species (ROS), which can cause oxidative stress and cellular damage (Ullah et al., 2023; Padmavathy et al., 2008).

7.1.1 Attachment to the Cell Membrane

The bacterial cell membrane's integrity and activity are compromised when IONPs connect to it, which ultimately results in bacterial cell death (Rudramurthy et al., 2016). Depending on the particular circumstances and bacterial strains involved, IONPs' antibacterial effect can use a variety of methods. Transport functions are hampered and exterior cell barriers are blocked as a result. Due to their high surface area to volume ratio and nanoscale size, IONPs can physically break bacterial cell membranes when they cling to them. The membrane may experience localized stress spots or

perturbations due to the nanoparticles, which could result in mechanical damage or structural abnormalities (Arias et al., 2018). IONPs can change the permeability of bacterial cell membranes through attachment and subsequent interaction (Armenia et al., 2018).

7.1.2 Membrane Disruption

As previously indicated, IONPs can interact electrostatically with bacterial cell membranes to cause detrimental oxidative stress in the bacterium by generating free radicals (Jayanthi et al., 2013). Furthermore, intracellular oxygen from aerobic bacteria oxidizes zero-valent iron, resulting in permanent oxidative cell damage. Furthermore, IONPs can physically harm the cell wall by entering the cell due to their small size, which restricts cellular development, replication, and even communication (Lee et al., 2008). Fe_2O_3 nanoparticles attach to the cell wall and even enter the cytoplasm of E. coli, where they concentrate and cause vacuole formation and cell wall breakdown, according to electron microscopy research (Armijo et al., 2020; Li et al., 2018) generating an inner membrane gradient that has a potent antibacterial effect on these bacteria (Gabrielyan et al., 2019). ROS cause genotoxic damage to DNA molecules (Kohanski et al., 2010). An rise in ROS levels may result from a decline in the activity of antioxidant system enzymes (SOD, catalase, and glutathione reductase). (Kaul et al., 2012).

The mercapto (-SH), amino (-NH), and carboxyl (-COOH) groups of proteins, including enzymes, can be bound by metal ions, resulting in inactivation or partial inhibition (Yu et al., 2015). Antibiotic-resistant bacteria present in operating rooms can have their expression of antibiotic resistance genes (ARGs) reduced by IONPs (AlMatar et al., 2018). It has also been documented that tiny nanoparticles can prevent DNA replication by deactivating topoisomerase (Guittat et al., 2003).

7.1.3 Enzyme Denaturation

(IONPs) have the capacity to denature and inhibit enzyme activity and demonstrated encouraging antibacterial action (Ali et al., 2016). IONPs have the ability to attach directly to enzymes, changing their three-dimensional structure and, consequently, their functioning (Vranish et al.,2018). The nanoparticles may bind to the enzyme's active sites or other crucial areas, preventing substrate binding and catalytic activity (Gole et al., 2001). Additionally, conformational changes in the structure of enzymes may be brought about by the interaction between IONPs and enzymes. These changes may cause the enzyme to become inactive or drastically lower its activity (Gao et al., 2017). In terms of the suppression of enzyme activity, IONPs may function as competitive inhibitors for specific enzymes by attaching to their active sites and blocking substrate molecules from accessing them (Akagi et al., 2006). Additionally, IONPs may bind to locations on

the enzyme other than the active site, changing the structure of the enzyme and decreasing its activity—a type of non-competitive inhibition (Miranda et al., 2011).

7.1.4 Electron Transfer Disruption

Numerous cellular functions, particularly energy production and preserving cellular redox equilibrium, depend on electron transport. Cellular malfunction and death may result from disruption of electron transmission. Iron oxide nanoparticles (IONPs) can disrupt electron transfer in a number of ways, including by directly interacting with redox-active proteins, particularly those found in the bacterial electron transport chain (ETC) (Ullah et al., 2023). This might cause electron flow to be blocked or diverted, which would cause the ETC to fail and produce less ATP. IONPs may experience redox cycling with cellular constituents such as flavins or NADH (Berg et al., 2010).

7.1.5 Antibiofilm Activities

IONPs affect their ability to adsorb and penetrate biofilms, the physicochemical characteristics of nanoparticles, such as surface charge and hydrophobicity, are crucial when assessing their antibiofilm activity (Morones et al., 2005). Compared to negatively charged IONPs, positively charged and neutral Fe_3O_4 nanoparticles have been demonstrated to decrease biofilm formation in *Streptococcus* mutants, the main cause of caries (Javanbakht et al., 2016). It has been noted that IONPs reduce the formation of alginate, an essential part of the exopolysaccharide of *P. aeruginosa* biofilm. At values between 0.8 and 64 μg/mL, this decrease is dose-dependent (Al-Shabib et al., 2018). Due to vibration damage, localized heat, and ROS production, superparamagnetic iron oxide nanoparticles (SPIONs) destroy biofilms and cause cell death (Kolen'ko et al., 2014). These elements cause bacteria to separate from a biofilm, bacterial cell wall destruction, membrane rupture, cell fusion, and death (Li et al., 2020).

The minimum inhibitory concentration (MIC) values ranging from a few micrograms per milliliter (μg/mL) to several hundred μg/mL are frequently reported in certain literature on the antibacterial activity of IONPs, as outlined below:

- A significant level of antibacterial activity is shown by low MIC values, which are less than 50 μg/mL (Jalab et al., 2021).
- MIC values in the middle range: 50–200 μg/mL (Armenia et al., 2018).
- High MIC values (over 200 μg/mL) signify lesser efficacy since they require a larger concentration of IONPs for antibacterial action (Al-Shabib et al., 2018).

It is crucial to emphasize that MIC values for iron oxide nanoparticles (IONPs) with antibacterial activity might differ depending on a number of variables, including the kind of bacteria, the size of the IONPs, the production process, and the experimental setup.

8. Biomedical Applications of IONPs

Regarding their origin, size, and composition, IONPs' toxicity and biocompatibility are crucial for their usage in biomedical applications. In biomedical applications, other factors including biodegradability and retention duration are crucial. This article describes the use of IONPs in biomedicine.

8.1 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is a powerful non-invasive modality that can produce high-resolution images of human anatomy based on the principles of Nuclear Magnetic Resonance (NMR); however, in some cases, the technique's sensitivity and effectiveness can be improved by using contrast agents. IONPs may be used in this situation. These nanoparticles' contrast properties change when they come into contact with particular biological organelles like endosomes and lysosomes (Billotey et al., 2003).

The practical applications of IONPs are significantly influenced by their retention time. The reduction in proton relaxation time, which is divided into T1 relaxation and T2 relaxation, provides the basis for how MRI contrast agents work. T1 relaxation is the time required for transverse magnetization to return to its initial state and longitudinal magnetism to reach 63% of its equilibrium value; a decrease in this time leads to an increase in positive contrast. T2 relaxation is the time needed for longitudinal magnetization to return to zero and transverse magnetism to decline to 37% of its initial magnitude; a reduction in this time promotes negative contrast. It is important to remember that the external magnetic fields used in MRIs usually have strengths between 1.5 and 3 Tesla. In this case, the IONPs' size, shape, and chemical makeup play a crucial role in influencing the T values. IONPs have mostly been used as T2 contrast agents up to this point (Qiao et al., 2009). Thermal breakdown techniques were used to create magnetite nanocrystals with spherical and faceted geometries, which the researchers compared. Their results showed that a significant improvement in relaxivity is correlated with an increase in the size of faceted nanoparticles. On the other hand, there was no discernible correlation between size and relaxivity for spherical nanoparticles. In conclusion, faceted nanoparticles exhibit better relaxivity than spherical ones (Smolensky et al., 2013).

8.2 Targeted Drug Delivery

IONPs have magnetic characteristics and compatible with biological systems, therefore they have well-known applications in the field of oncology. Targeted drug delivery is one of the main applications that greatly improves the effectiveness of cancer treatments. IONPs minimize damage to surrounding healthy tissues by precisely targeting cancerous cells through their interactions with biomolecules at the cellular level. Additionally, IONPs facilitate the magneto-mechanical activation of cell surface receptors, which enhances therapeutic results using techniques like magnetic hyperthermia, in which localized heat effects cause tumor cells to undergo apoptosis. Usually, only a small portion of medications that are administered orally or intravenously reach the affected organ. Targeted medication delivery increases the therapeutic agent's concentration in the targeted tissues and facilitates the body's ability to pass physiological barriers through a variety of active targeting techniques. Specifically, IONPs used in pharmacological delivery systems are a reliable approach in the field of cancer treatments. As a result, conventional chemotherapeutic methods might have less side effects since IONPs enable the targeted delivery of medications and minimize the necessary dosages (Cao et al., 2008).

Modified IONPs can act as carriers, making it easier for different pharmaceutical drugs to be distributed throughout the body. IONPs will be enclosed in a biocompatible, functionalized shell in order to accomplish this goal. The size of IONPs is crucial in this situation; they must be small enough to pass through vascular structures but larger than 10 nm to avoid quick systemic clearance. Therefore, the ideal size range should be determined to be between 10 and 100 nanometers (Laurent et al., 2008).

8.3 Tissue Engineering

Generating functional replacement tissues with noteworthy characteristics when combined with biomaterials is the aim of tissue engineering. In this regard, the application of cells and the control of their functions provide significant difficulties in the tissue engineering sector (Zhao et al., 2015).

The use of magnetic cells appears to be a successful solution to this problem. An external magnetic field has the ability to modify and regulate these cells, hence controlling their assembly. Ito et al. used magnetic force to successfully create a three-dimensional cell culture. Together with the cells, they created heterotypic multilayered cell sheets that successfully increased albumin secretion. In a different study, Heidari et al. created a scaffold for bone tissue engineering using

IONPs, hydroxyapatite, and chitosan. The size range of the produced IONPs was 10–40 nm, and the magnetic crystal size was roughly 23.5 nm. The control of cell adhesion has recently been made possible by the use of peptide-modified magnetite liposomes as selective labels for cell targeting, made possible by computational techniques (Ito et al., 2007). In order to promote osteogenesis and angiogenesis in lumbar degenerative disk disease (DDD), Wang et al. describe a novel magnetofection method that uses iron oxide nanoparticles (IONPs) for targeted gene delivery. The technique greatly increases the transfection efficiency of therapeutic miR-21 into human umbilical endothelial cells and bone marrow mesenchymal stem cells by mixing electromagnetic fields (EMF) with IONPs. This novel technique has the potential to be a successful treatment strategy for orthopedic problems since it not only enhances cellular responses but also activates important pathways (Wang et al., 2023).

9. Conclusion

In conclusion, iron oxide nanoparticles represent a highly promising class of nanomaterials due to their distinctive magnetic properties, stability, and wide range of applications. Various synthesis techniques have been developed to produce IONPs with controlled size and morphology; however, each method presents certain limitations in terms of cost, scalability, and environmental impact. In this context, green synthesis using biological sources, particularly Ricinus communis, has emerged as a sustainable and eco-friendly alternative. The presence of diverse phytochemicals in *Ricinus communis* plays a crucial role in the reduction and stabilization of nanoparticles, enhancing their biocompatibility and functional properties. Additionally, the plant exhibits significant pharmacological activities, further supporting its potential in biomedical applications.

Despite these advancements, challenges such as reproducibility, toxicity concerns, and lack of standardized protocols still need to be addressed. Future research should focus on optimizing green synthesis methods, improving nanoparticle stability, and expanding their applications in targeted drug delivery, diagnostics, and environmental remediation. Overall, the integration of nanotechnology with green chemistry principles holds great promise for the development of safe, efficient, and sustainable nanomaterial.

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