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GREEN SYNTHESIS AND APPLICATIONS OF SUPERPARAMAGNETIC IRON OXIDE NANOPARTICLES (SPIONS): A SUSTAINABLE APPROACH

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ABSTRACT

Iron oxide nanoparticles, particularly superparamagnetic iron oxide nanoparticles (SPIONs), have attracted considerable attention due to their unique magnetic properties, biocompatibility, and potential in biomedical and environmental applications. Traditional physical and chemical synthesis methods involve hazardous reagents and energy-intensive processes. Green synthesis, especially using plant extracts, offers a safer, eco-friendly, and cost-effective alternative. This review explores the various forms of iron oxide, their structural and magnetic characteristics, and recent advances in plant-mediated synthesis. The potential applications in imaging, drug delivery, environmental remediation, and biosensing are also discussed, emphasizing the advantages of sustainable nanoparticle production.

INTRODUCTION

Iron oxides exist in several crystalline forms, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_2O_3), each exhibiting distinct physicochemical properties. The magnetic nature of these nanoparticles, particularly superparamagnetic behavior in the 5–20 nm size range, makes them valuable in targeted drug delivery, magnetic resonance imaging (MRI), hyperthermia treatment, and environmental applications. The need for eco-friendly synthesis methods is critical due to the toxicity and environmental burden of conventional methods.

1. LITERATURE REVIEW

This study highlights the synthesis of iron nanoparticles using plant-based reducing agents, demonstrating an eco-friendly alternative to traditional chemical routes. The authors successfully employed aqueous plant extracts to reduce iron salts into nanoparticles. Key advantages include non-toxic byproducts, room-temperature synthesis, and effective particle stabilization through biomolecules. The work emphasizes the potential of green-synthesized iron nanoparticles in water purification and heavy metal adsorption by Abdelmonem, A. M., & Amin, R. M [1].

This research explored the use of treated sewage effluent in the irrigation of Tipuana speciosa, evaluating its effect on plant growth and soil health. Though not focused directly on nanoparticle synthesis, the study indirectly supports the concept of resource recycling and its compatibility with plant systems—both of which are foundational to green synthesis approaches. It further highlights the plant's tolerance to effluent components, a trait that could be harnessed for nanoparticle biosynthesis by Ali, H. M et al [2]. This paper presents a comprehensive study on the synthesis, characterization, and environmental utility of iron oxide nanoparticles. The authors discuss catalytic activities and pollutant removal efficiencies in water treatment systems. While the synthesis method was not entirely green, the paper sets a benchmark for performance evaluation and comparative studies with green-synthesized alternatives. It highlights the significant potential of iron oxide NPs in catalysis, especially for degradation of organic pollutants by Bokare, A. D., et al [3].

This study focuses directly on eco-friendly synthesis techniques for iron oxide nanoparticles. Using plant materials as both reducing and capping agents, the authors achieved stable and uniform nanoparticles under mild conditions. They reported good adsorption properties, suggesting utility in wastewater treatment and soil amendment. The research advocates for the use of abundant, low-cost, and renewable plant resources in nanomaterial production by Giwa, A., et al [4]. Hosseinian et al

[5] explored biological synthesis methods for nanoparticles using microorganisms and plant extracts. They emphasized eco-friendliness, cost-effectiveness, and the ability to produce highly stable nanoparticles with minimal energy input. Huey et al. [6] reported on the magnetic properties of SPIONs synthesized through green routes, revealing that environmentally benign methods can yield nanoparticles with comparable performance to chemically synthesized counterparts. Khan et al [7] reviewed various plant and microbial approaches for synthesizing iron oxide nanoparticles and discussed their use in drug delivery, biosensors, and wastewater treatment. Mody et al [8] discussed structural tunability and magnetic responsiveness of SPIONs for targeted drug delivery systems, showing controlled release behavior and improved bioavailability. Namvar et al [9] demonstrated the efficiency of plant-mediated synthesis in producing stable, crystalline magnetic nanoparticles, particularly using marine and herbal plants. Ramimoghadam et al [10] synthesized iron oxide nanoparticles electrochemically, showing high crystallinity and surface area with potential for catalysis and remediation. Satyanarayana & Ramesh Chandra [11] discussed the use of nanomaterials including SPIONs in environmental remediation, especially for wastewater purification and pollutant adsorption.
Zhu et al [12] synthesized functionalized SPIONs for gas hydrate control, illustrating their stability, superparamagnetic and environmental resilience. Saifulazhar et al [13] conducted a systematic review on biosynthesized SPIONs in oral cancer treatment, reporting their efficacy in targeted therapy, reduced toxicity, and potential use in "green dentistry. Shishodia et al [14] employed fruit peel extracts and microwave-assisted green synthesis for surface-functionalized SPIONs, showing promise in MRI contrast imaging and photodynamic therapy. Bordbar & Ghasemi [15] offered an extensive review of SPION synthesis via sustainable methods and discussed their use in catalysis, pollutant removal, and biomedical applications. Hassan & Husein [16] presented a mini review on SPIONs for biomedical applications, highlighting their roles in imaging, magnetic therapy and drug delivery systems. Singh & Singh [17] provided a comprehensive overview of the structural, magnetic, and biomedical properties of SPIONs, including imaging and hyperthermia. Akintelu et al [18] reviewed the use of green-synthesized SPIONs in biomedical and environmental applications, particularly highlighting heavy metal adsorption. Ahmad & Khan [19] presented a broad review of iron-based nanoparticles synthesized via green chemistry for use in environmental decontamination. Pérez-López et al [20] synthesized SPIONs using Eucalyptus globulus extract and demonstrated their effectiveness in removing heavy metals from agricultural soils. Srivastava et al [21] demonstrated green-synthesized SPIONs for breast cancer treatment, emphasizing biocompatibility and selective cytotoxicity.

3. FORMS AND PROPERTIES OF IRON OXIDE NANOPARTICLES

3.1 TYPES OF IRON OXIDE NANOPARTICLES

- **MAGNETITE (FE_3O_4):** A black iron oxide with an inverse spinel structure. It contains both Fe^{2+} and Fe^{3+} ions and exhibits strong magnetic properties.
- **MAGHEMITE (Γ-FE_2O_3):** A red-brown iron oxide formed by oxidation of magnetite. It has a similar spinel structure but contains only Fe^{3+}.
- **HEMATITE (A-FE_2O_3):** A reddish, weakly magnetic oxide with a rhombohedral structure, used in catalysis and pigments.

3.2 CRYSTALLINE STRUCTURE

Magnetite possesses a face-centered cubic (fcc) lattice where Fe^{2+} and Fe^{3+} ions occupy both octahedral and tetrahedral sites, resulting in unique electronic interactions. Maghemite shares a similar spinel framework but is fully oxidized, while hematite has a hexagonal close-packed arrangement. These structural variations significantly influence the physical and magnetic behavior of nanoparticles.

3.3 SUPERPARAMAGNETISM AND BIOMEDICAL RELEVANCE

Nanoparticles of magnetite and maghemite in the 10–20 nm range exhibit superparamagnetic—a state where magnetic domains are so small that thermal fluctuations randomize their orientation in the absence of an external field. This property is critical for biomedical uses like MRI contrast agents and magnetic hyperthermia, as it prevents particle aggregation and ensures safe interaction with biological systems.

3.4 PARTICLE SIZE AND SURFACE CHEMISTRY

The size of iron oxide nanoparticles strongly influences their magnetic properties, stability, and reactivity. Smaller particles (<20 nm) offer higher surface-to-volume ratios, enhancing their interaction with surrounding media. Surface functionalization using biocompatible agents like polyethylene glycol (PEG), dextran, or plant phytochemicals further improves dispersion, reduces toxicity, and enables targeted delivery in therapeutic applications.

3.5 GREEN SYNTHESIS OF IRON OXIDE NANOPARTICLES

Green synthesis involves the use of biological systems such as plants, algae, bacteria, and fungi to reduce and stabilize metal ions. Plant extracts, in particular, contain secondary metabolites such as polyphenols, flavonoids, and alkaloids that act as natural reducing agents. This method eliminates the use of hazardous chemicals, making it an environmentally sustainable alternative.
Recent studies have demonstrated successful synthesis of iron oxide nanoparticles using extracts from various plants like green tea, neem, and eucalyptus. These nanoparticles exhibit excellent stability and uniformity, with properties comparable to those synthesized chemically.

Table 1: Comparison Between Green and Conventional Synthesis Methods of Iron Oxide Nanoparticles

Aspect	Green Synthesis	Conventional Synthesis
Reducing Agents	Plant extracts, bacteria, fungi	Hydrazine, sodium borohydride, chemical precursors
Stabilizers	Biomolecules in extract	Surfactants or synthetic polymers
Reaction Conditions	Ambient temperature and pressure	High temperature, inert atmosphere
Environmental Impact	Eco-friendly, biodegradable byproducts	Toxic byproducts, non-biodegradable waste
Cost	Low, due to renewable sources	High, due to energy input and chemicals
Biocompatibility	High	Low to moderate
Scalability	Emerging, requires optimization	Well-established

4. CHALLENGES AND FUTURE DIRECTIONS

Despite promising results, green synthesis faces challenges such as scalability, reproducibility, and limited control over nanoparticle size and morphology. Further research is needed to standardize protocols, explore novel plant sources, and assess the long-term biocompatibility of these nanoparticles.

CONCLUSION

Green synthesis of iron oxide nanoparticles represents a significant advancement in sustainable nanotechnology. These nanoparticles offer immense potential in various sectors, especially in medicine and environmental science. Continued exploration of plant-mediated synthesis pathways and comprehensive toxicity assessments will be key to commercial and clinical translation.

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