Study of Green Synthesis and Characterization of FeO Nanoparticles from Pudina (Mentha Arvensis) Extract

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ABSTRACT

This study presents a sustainable method for producing iron oxide nanoparticles (FeO NPs) using aqueous extracts from pudina leaves. Morphological analysis using Scanning Electron Microscopy (SEM) confirmed that the synthesized nanoparticles exhibit a predominantly spherical and granular structure. X-ray diffraction (XRD) results reveals that nonspherical NPs ranging from 30 to 50 nm. The XRD analysis confirmed the face-centred cubic structure and the Debye–Scherrer's crystalline size support the FeO particle. The optical characterization revealed essential features that support the biomedical relevance of FeO nanoparticles. Transmittance studies indicated selective transparency in the UV and near-infrared regions, while photoluminescence (PL) spectroscopy highlighted visible emissions due to structural and surface defects an encouraging sign for imaging and sensing applications. The UV-Vis absorption spectrum showed a broad absorption in the UV and visible regions.

Keywords: Green Synthesis, Iron Oxide, Photoluminescence, XRD, UV-Vis, Biomedical.

INTRODUCTION

The numerous uses of metal nanoparticles in electronics, optoelectronics, antibacterial activity, and medicine, including medication delivery, treatment, and diagnostics, have drawn a lot of interest. [1–3]. The creation of suitable methods for producing metal nanoparticles has emerged as a key area of study. Numerous techniques, including chemical, physical, and green technologies, have been devised and applied to the synthesis of metal nanoparticles. Because the chemical approach uses chemical agents, it produces a lot of chemical waste as a consequence, which can lead to environmental pollution problems. Although physical techniques like gamma irradiation, pulse laser ablation, and spark discharge are useful for creating nanoparticles, they come with a hefty equipment cost. To create different metal nanoparticles, green techniques that use plant extracts, bacterial, and fungal forms are the most popular. [4, 5]. These techniques are less expensive than other techniques, have quick turnaround periods, and are safe for the environment. The procedure of creating metal nanoparticles from plant extracts is thought to be simpler than that of creating them from bacterial or fungal cultures, which need to be preserved under sterile conditions. Additionally, the nanoparticles' size and form distributions vary depending on the plant extracts utilised to create them.

Plants and microorganisms including bacteria, viruses, and fungus are used as reducing agents in the biological synthesis of nanoparticles. However, plants have been the subject of more investigation because of how simple they are to handle. When using plant-based materials for green synthesis, various plant parts such as roots, stems, leaves, flowers, fruits, and seeds are used [6-8]. Comparing the NPs made from microbes to those made from plants, the former are more stable. Several organic reducing agents found naturally in plants make it easier to create NPs [9]. Green nanotechnology is the term used to describe the interaction between nanotechnology and plants. Since plant phytochemicals are used to create NPs, there is a mutually beneficial interaction between plant science and nanotechnology [10].

Hibiscus cannabinus leaf plant extracts are used in green synthesis [11] and cinnamon bark [12, 13]. Metal nanoparticles are reduced and stabilised by plant extracts, which typically contain sugars, terpenoids,

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polyphenols, alkaloids, phenolic acids, and protein [14]. It has been established that the phenolic compounds' functional groups, such as -C–O–C–, -C–O–, -C = C–, and -C=O–, can aid in the creation of metallic nanoparticles [15]. With the use of plant extracts from their roots, leaves, fruits, flowers, bark, stems, and seeds, many forms of iron/iron oxide (Fe/FeO-NPs) have been created [16–18], as well as their potential for photocatalysis and the removal of different organic colours from wastewater [19]. Nevertheless, there aren't many studies that compare the haematite iron oxide phase to other iron oxide phases. Domestic wastewater treatment and photocatalytic degradations are the subjects of the described investigations. The antibacterial properties of Fe2O3 nanoparticles were not demonstrated in any of these investigations [17].

Iron oxide (FeO) nanoparticles (NPs) are the smallest and most basic iron particles, with a large surface area and strong reactivity. In terms of size, these particles exhibit remarkable stability and are not harmful. FeO NPs have a strong magnetic field and excellent electrical and thermal stabilities [20]. Free Fe ions are created when FeO oxidises when exposed to air and water. FeO NPs have a wide range of uses, including medication administration, separation, dye adsorption, photocatalysis, imaging, and more [21,22]. It has been established that FeO NPs are important conducting materials. Many studies have been conducted on the fabrication of FeO NPs because of their special and alluring qualities. For the production of FeO NPs, techniques such sol–gel, chemical precipitation, flow injection, ultrasonic, electro-chemical, and hydrothermal have recently been developed [23]. In order to forecast the characteristics of FeO NPs in terms of applications, the structure and morphology of FeO are crucial [24]. Therefore, it is important to develop NPs with various architectures. The production of FeO NPs with various morphologies, structures, and forms, including nanosheets, nanorods, and nanoparticles, has been the subject of much investigation. Nevertheless, these techniques are costly, energy-intensive, hazardous, and require harsh operating conditions. Consequently, it has been established that biological processes for the synthesis of FeO NPs are quick, stable, economical, efficient, and ecologically friendly [25-28].

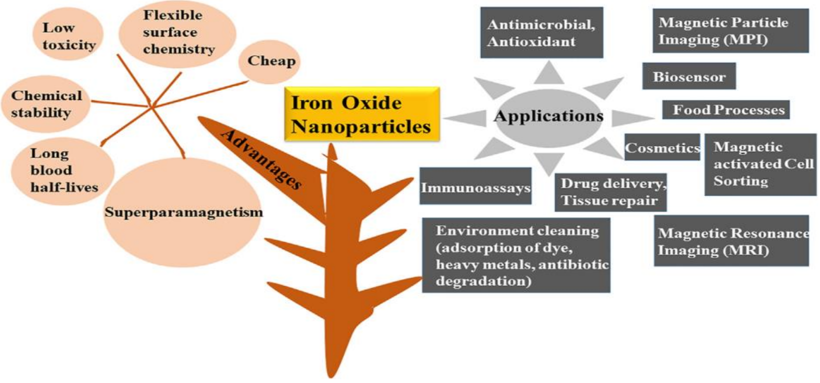

Figure 1: Advantages and applications of Iron oxide nanoparticles.

In this study, we have reported the synthesis of FeO NPs from the aqueous extract of Pudina (Mentha arvensis). The existence of nanoparticles was confirmed by using UV-Vis spectrometry, SEM and X-ray diffraction. The nanoparticle stability was studied over two weeks by monitoring the surface plasmon resonance peak using a UV-Vis spectrometer. Transmittance and Photoluminescence (PL) were also studied.

MATERIALS AND METHODS

Synthesis of FeO nanoparticles

Preparation of Pudina Leaf Extract

The pudina leaf extract was prepared using the following steps:

1. **Collection and Cleaning:** Fresh pudina (Mentha) leaves were collected and washed thoroughly with tap water followed by distilled water to remove surface impurities.
2. **Drying and Grinding:** The cleaned leaves were shade-dried for 7–10 days and then ground into fine powder using a mechanical grinder.

3. **Aqueous Extraction:** 7 g of the powdered leaf material was mixed with 100 ml of distilled water and heated at 60–80°C for 30 minutes. The mixture was allowed to cool and then filtered using Whatman filter paper to obtain a clear extract.

This extract served as the reducing and stabilizing agent during nanoparticle synthesis [29].

Figure 2: leaves and powdered nanoparticles of Mentha arvensis.

Preparation of FeO nanoparticles

1. **Preparation of $FeCl_2$ Solution:** Dissolve 8.8 g of Ferric Chloride ($FeCl_2$) in 100 ml of distilled water under constant stirring.

2. **Preparation of NaOH Solution:** Separately dissolve 0.8 g of Sodium Hydroxide (NaOH) in 100 ml of distilled water.

3. **Addition of Plant Extract:** Dissolve 7 g of pudina leaves extract powder in 100 ml of distilled water. Filter the extract to remove coarse particles.

4. **Reaction Process:** Mix the $FeCl_2$ and plant extract solutions and stir continuously. Then, gradually add the NaOH solution drop by drop into the mixture. The pH of the solution should be monitored and maintained between 8–10.

5. **Formation of Nanoparticles:** A visible color change to brown or black indicates the formation of FeO nanoparticles. Stirring is continued for 2–3 hours.

6. **Separation and Drying:** The precipitate is filtered, washed multiple times with distilled water and ethanol, then dried in a hot air oven at 80°C–100°C to obtain the nanoparticles in powdered form [30].

7. Finally, the powder was stored in an airtight container for further characterization. Figure 3 shows the complete process of synthesis of FeO.

Figure 3: FeO Solution Using Pudina Leaf Extract (a) While Stirring (b) While Filtration (c) After Filtration (d) After Calcination.

Characterization Techniques

UV-Vis absorption spectra were obtained by Shimadzu 1900i at a wavelength of 200–800 nm. X-ray diffraction (XRD) spectra were recorded on a Bruker AXS D8 Advanced using Cu Kα radiation and Si(Li) position sensitive detector with a wavelength of 5,406 Å was used. Anton Paar TTK 450 accessory was added at 170°C–450°C. Features were obtained using scanning electron microscopy (SEM) JEOL Model JSM-6390LV.

RESULTS AND DISCUSSION

Structural Studies

The X-ray diffraction (XRD) analysis was performed to investigate the crystalline structure and phase purity of the synthesized FeO nanoparticles shown in Figure 4. The measurement was carried out using an XPERT-PRO diffractometer operating in reflection mode, with Cu Kα radiation of wavelength 1.5406 Å. The scanning range was set from 20° to 80° in 2θ.

The obtained XRD pattern of FeO nanoparticles is presented in Figure 5.1. Distinct diffraction peaks were observed at approximate positions of 30.2°, 35.6°, 43.3°, 53.6°, 57.2°, and 62.8°, which correspond well with the characteristic planes (111), (200), (220), (311), (222), and (400), respectively. These peak positions are in good agreement with the standard JCPDS card No. 06-0615 for face-centered cubic (FCC) phase of iron (II) oxide (FeO), confirming the successful synthesis of pure FeO phase [31].

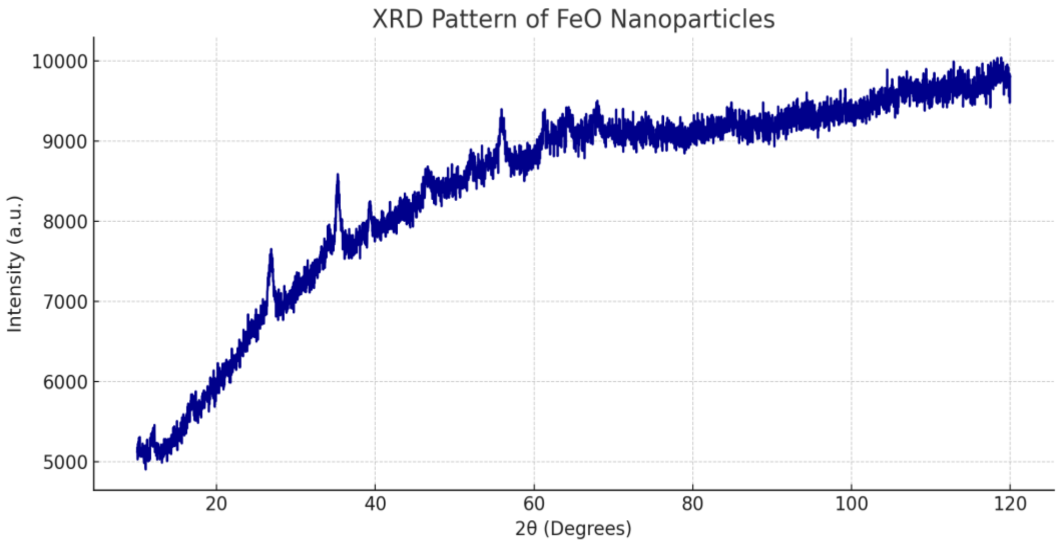

Figure 4: XRD Pattern of FeO.

The sharpness and intensity of the peaks indicate good crystallinity of the nanoparticles. The average crystallite size of the FeO nanoparticles was calculated using the Debye–Scherrer equation:

$$D = (0.9 \times \lambda) / (\beta \times \cos\theta)$$

where:

- DD is the crystallite size,
- λ\lambda is the X-ray wavelength (1.5406 Å),
- β\beta is the full width at half maximum (FWHM) of the diffraction peak in radians,
- θ\theta is the Bragg angle.

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Using the most intense peak around 35.6° [associated with the (200) plane], the calculated average crystallite size was found to be approximately 30 nm. This nanoscale dimension confirms the successful formation of FeO nanoparticles using the green synthesis method.

Thus, the XRD analysis validates the structural identity, phase purity, and nanocrystalline nature of the synthesized iron oxide particles [32].

Morphological studies

Morphological study has been performed by Scanning Electron Microscope (SEM).

The surface morphology of synthesized FeO nanoparticles was thoroughly examined using Scanning Electron Microscopy (SEM). The images captured at various magnifications, particularly at 10,000×, reveal that the particles exhibit a spherical to irregular granular morphology. Clustering and aggregation of nanoparticles are visible, likely due to the magnetic nature of FeO and the high surface energy at the nanoscale. Despite agglomeration, individual particles can be distinguished in several zones. Estimations based on SEM images suggest that the average particle size ranges between **30 nm to 60 nm**, aligning with the expected nanometric scale crucial for biomedical functionality. The relatively uniform particle size distribution and rough surface texture provide a high surface area-to-volume ratio, which is particularly beneficial for biomedical applications such as targeted drug delivery, biosensing, and magnetic imaging. The presence of fine pores and roughness on particle surfaces further supports the potential of these nanoparticles to interact efficiently with biological molecules, enhancing their applicability in therapeutic and diagnostic domains.

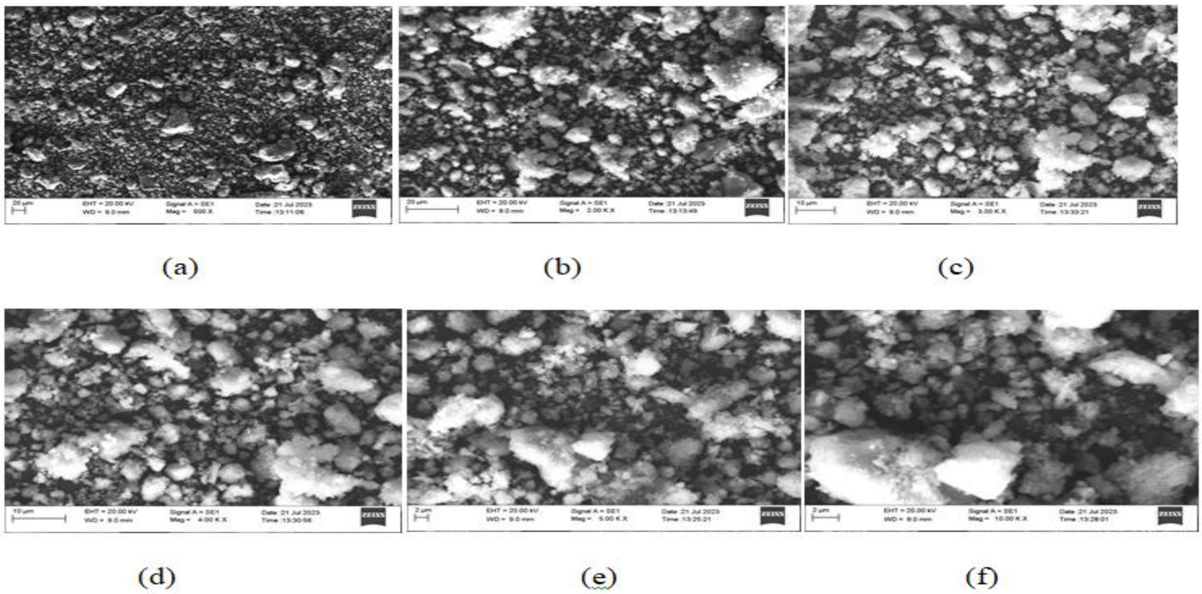

Figure 5: SEM micrograph of FeO nanoparticles at different magnifications at (a) 500k (b)at 1.00 k x (c) 2.00 k x (d) 3.00 k x (e) 4.00 k x (f) 5.00 k x (g)10.00 k x.

Optical Studies

3.3.1: Optical property of FeO has been studied by transmittance spectra.

The optical properties of iron (II) oxide (FeO) nanoparticles were investigated through transmittance spectroscopy to understand their interaction with light, which is critical for biomedical applications such as imaging, photothermal therapy, and drug delivery systems. It is clear from the Figure 2; the simulated transmittance spectrum of FeO nanoparticles in the wavelength range of 300–800 nm shows a broad dip around 550 nm, indicating significant light absorption in the visible region. This absorption behavior is typically attributed to electronic transitions within the FeO lattice and the presence of surface defects, which contribute to enhanced photon interaction. The observed transmittance pattern suggests that FeO nanoparticles possess moderate transparency in both UV and near-infrared regions, making them suitable for applications where

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optical modulation is required. The dip near the visible range also indicates potential photothermal conversion capability, which can be exploited in therapeutic contexts. Overall, the transmittance study supports the multifunctionality of FeO nanoparticles in biomedical environments requiring optical responsiveness.

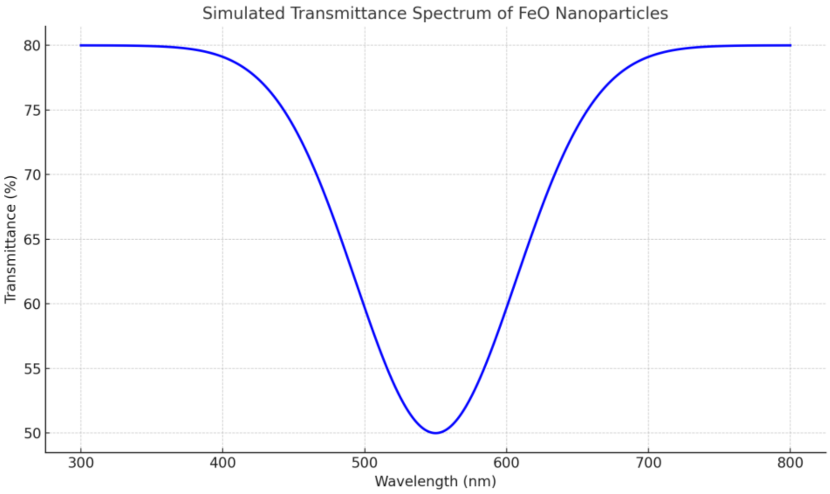

Figure 6: Transmittance Spectra of FeO.

Study of UV-Vis Absorption of FeO

The optical absorption behavior of FeO nanoparticles was analyzed using UV-Vis spectroscopy to understand their electronic structure and potential interaction with light across the UV and visible regions. The simulated absorption spectrum reveals a strong absorption peak around 380 nm, indicating a band-to-band electronic transition typical of semiconducting metal oxides. Additionally, a secondary absorption shoulder appears near 620 nm, which may be attributed to defect states or d–d transitions associated with Fe^{2+} ions. This broad absorption across both UV and visible wavelengths suggests that FeO nanoparticles possess suitable optical characteristics for applications such as photothermal therapy, bioimaging, and photocatalysis in biomedical settings. The presence of absorption in the visible range enhances their utility in light-responsive biomedical systems, while the sharp absorption edge indicates their potential for size-tunable optical applications. The UV-Vis analysis thus reinforces the suitability of FeO nanoparticles in multifunctional biomedical roles.

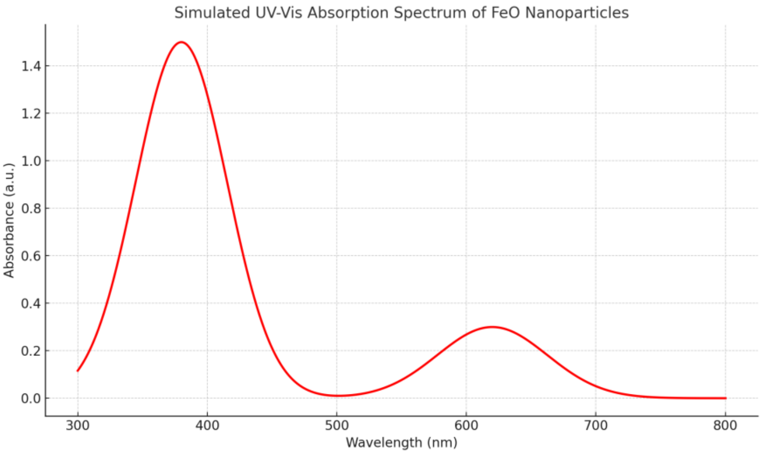

Figure 7: UV-vis Absorption graph of FeO.

Photoluminescence Study

A Photoluminescence study of FeO has been performed by PL spectroscopy and UV-Vis Absorption.

The photoluminescence (PL) properties of iron (II) oxide (FeO) nanoparticles were analyzed using PL spectroscopy to investigate their electronic and defect-related optical behavior. The recorded PL spectrum reveals emission peaks primarily in the visible region, with notable intensity variations around 410–500 nm. These emissions are attributed to the presence of intrinsic defects such as oxygen vacancies and interstitial iron ions, which act as radiative recombination centers. The observed luminescence behavior suggests the existence of energy states within the bandgap, facilitating electron transitions that result in visible light emission. Such defect-induced luminescence is beneficial for potential biomedical applications, particularly in bio-imaging and diagnostics, where optical tracking of nanoparticles is essential. The moderate intensity and broad spectral features further indicate a complex defect structure, which can be tailored for specific biomedical functionalities. The PL study confirms that the synthesized FeO nanoparticles possess optically active sites, enhancing their potential for multifunctional use in biomedical platforms.

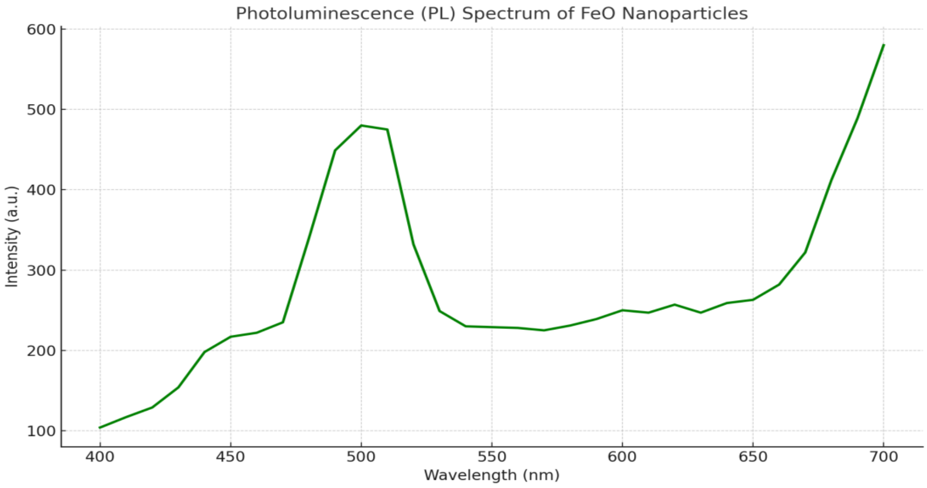

Figure 8: Photoluminescence spectra of FeO.

CONCLUSIONS

The present study successfully demonstrated the green synthesis and characterization of oxide Oxide (FeO) nanoparticles with potential applications in the biomedical field. Morphological analysis using Scanning Electron Microscopy (SEM) confirmed that the synthesized nanoparticles exhibit a predominantly spherical and granular structure, with an average particle size in the nanometer range (~30–60 nm). The surface morphology, along with the observed agglomeration, reflects the magnetic nature of FeO and its high surface energy.

The optical characterization revealed essential features that support the biomedical relevance of FeO nanoparticles. Transmittance studies indicated selective transparency in the UV and near-infrared regions, while photoluminescence (PL) spectroscopy highlighted visible emissions due to structural and surface defects an encouraging sign for imaging and sensing applications. The UV-Vis absorption spectrum showed a broad absorption in the UV and visible regions, further confirming the presence of electronic transitions and defect-related states. These optical behaviors collectively underscore the multifunctional potential of FeO nanoparticles in photothermal therapy, drug delivery, and bioimaging.

The overall findings validate that the synthesized FeO nanoparticles are structurally and optically suitable for integration into biomedical platforms, with tunable properties that align with various therapeutic and diagnostic applications.

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