

Original Article

GREEN SYNTHESIS OF α -Fe₂Cl₃ IRON OXIDE NANOPARTICLES: EFFECT OF TEMPERATURE AND PRECURSOR CONCENTRATION

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ABSTRACT

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This study demonstrates an eco-friendly and sustainable method for synthesizing α -Fe₂Cl₃ nanoparticles (IONPs) utilizing leaf extract from *P. atlantica*. The concentration of FeCl₃ ranged from 0.1 to 0.5 M, and the reaction temperature varied between 25 and 80°C. FTIR analysis showed that the plant chemicals in the extract helped stabilize the nanoparticles, and XRD analysis confirmed that the nanoparticles were pure α -Fe₂Cl₃ phase and had a crystal structure. FESEM analysis revealed that the size of α -Fe₂Cl₃ varied with increasing concentration, measuring from 31.6 ± 1.48 nm to 97.14 ± 10.47 nm and from 66.92 ± 1.65 to 85.25 ± 3.02 nm with increasing temperature. Particle size increased with both parameters, and some agglomeration was observed. UV-Vis spectroscopy showed that the α -Fe₂Cl₃ exhibit indirect band gaps, and bandgap energies changed with particle size, where larger particles had slightly lower band gaps. These results demonstrate that simple adjustments in precursor concentration and temperature allow for precise control over nanoparticle properties, and they indicate that this plant-based synthesis provides a method for creating functional IONPs that could be used in catalysis, environmental cleanup, and nanotechnology.

Keywords: green synthesis, α -Fe₂Cl₃, *P. atlantica* extract, tuning bandgap.

1. INTRODUCTION

Nowadays, science has gained an interest in the nanomaterial field because of various applications in medicine, agriculture, and environmental remediation. This interest stems primarily from their unique properties, including their nanoscale size in comparison to the bulk material (Ashrafi-Saiedlou, 2025). Nanoparticles (NPs) can be synthesized by physical and chemical methods, but these approaches often need high temperatures, dangerous chemicals, and complicated reaction conditions. This procedure means more energy use, environmental problems, and less compatibility with living things. To overcome these limitations, green synthesis methods that use biological pathways have gained high attention. These methods use natural extracts and biological parts from plants and microbes. They are a green, cost-effective, and eco-friendly way to form nanoparticles (Hussain *et al.*, 2023; Shabbir *et al.*, 2023; Venkatachalam, 2021).

Out of various nanoparticles, synthesizing plant-based iron oxide (IO) nanoparticles gained significant attention, especially in biomedical fields in imaging, drug delivery, antimicrobial activity, and hyperthermia-based cancer therapy. Using a type of plant that is rich in bioactive molecules helps synthesize IONPs by reducing and stabilizing agents (Aida *et al.*, 2023). In this green synthesis method, FeCl₃ is employed as the iron precursor because it easily dissolves in water to release Fe³⁺ ions, which allows iron oxide nanoparticles to form with a certain size and shape (Persson 2018). IONPs have been known as “nanozymes,” owing to their intrinsic enzyme-like catalytic activities (Priya *et al.*, 2021; Zúñiga-Miranda *et al.*, 2023). Out of various IONPs, hematite (α -Fe₂Cl₃) nanoparticles have distinct magnetic, electrical, and optical properties compared to hematite in bulk form. The way they act changes because they are small, have a lot of surface area, and have imperfections on their surfaces. This work

focuses on manufacturing and analyzing hematite nanoparticles since they have unique features that make them helpful in catalysis, magnetic devices, and electronics (Ali 2018).

Priya *et al.* (2021) reviewed several types of plants for synthesizing in green approaches and highlighted that phytochemical compounds present in plant extracts play an important role in controlling particle size, crystallinity, and band gap tuning, thereby enhancing the suitability of iron oxide nanoparticles for photocatalytic and biomedical applications. Choosing a reactive precursor under the right temperatures, it plays a critical role in synthesizing nanoparticles and their characteristics. As an example, temperature during the nucleation and growth influences crystalline, morphology, size, structure, and phase of nanoparticles. In recent studies, optimizing these parameters by using plants such as *Egeria densa* and *C. nigricans* plant extract is crucial during synthesizing nanoparticles under required applications (Gobi *et al.*, 2023; Priya *et al.*, 2021; Yekeen, 2025). Also, Aida *et al.* (2023) synthesized hematite (α -Fe₂Cl₃) nanoparticles using *Hibiscus* plant extract with a concentration of 0.1M of iron chloride at room temperature through an eco-friendly synthesis method.

Recently, researchers looked forward to different species of plants, for instance, demonstrating the potential of *Pistacia* species in the green synthesis of metallic nanoparticles due to their bioactive-rich phytochemical compounds. Alabrahim *et al.* (2025) confirmed that *Pistacia* species extracts contain various phenolic, flavonoids, and tannins bioactive compounds. These compounds help control particle growth, morphology, and optical properties, while also providing potential biological activity, making *Pistacia* extracts a valuable plant source for eco-friendly nanoparticle fabrication (Alabrahim *et al.*, 2025).

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In 2024, Hasanzadeh et al. provided experimental work on *Pistacia atlantica* (*P. atlantica*) leaf extract and the way it can reduce Fe^{3+} iron ions to form IONPs to remove harmful molecules such as Cr(VI) (hexavalent chromium) from a solution. This ensures that *P. atlantica* is essential in environmental remediation potential. These findings contribute to the suitability of *P. atlantica* to have good control over synthesizing iron oxide nanoparticles for various applications under optimized conditions (Hasanzadeh *et al.*, 2024). Several plant species from the Kurdistan Region have been utilized due to their rich phytochemical composition (Hama Kareem & Abdulla, 2023; Omar & Mohammed, 2023).

Most studies on IONPs synthesis from plant extracts only look at the effect of one factor. To address this, the present study examined how the amount of FeCl_3 precursor and the temperature during the process together affect the formation and properties of pure $\alpha\text{-Fe}_2\text{Cl}_3$.

The current study seeks to synthesize $\alpha\text{-Fe}_2\text{Cl}_3$ through a green, plant-mediated method using extract from *P. atlantica* leaves, which is rich in polyphenols and flavonoids. The results of this study offer significant insights into the optimization of synthesis conditions for prospective structural, morphological, and optical characteristics.

2. METHODS AND MATERIALS

Plant Collection:

Pistacia atlantica subsp. *Kurdica* (*P. atlantica*) leaves were collected from Baroshka Saddini village in July 2024, located in northern east of Duhok City in the Kurdistan Region of Iraq. After collecting the leaves, they were rinsed with tap and distilled water to remove impurities and then air-dried at room temperature (25–30°C) until fully dried.

Preparation of Extract:

The dried leaves were ground into a fine powder using a clean electric grinder. A fixed amount of the powder, 10 g, was mixed with 100 mL of distilled water in a beaker. The mixture was subjected to extraction using a temperature-controlled ultrasonic bath (ultrasonic cleaner) equipped with a digital timer and heater and made to undergo sonication for about 30 minutes at a temperature of 60°C, a power of 150 W, and a nominal frequency of 40 kHz, which is widely used for plant extraction of bioactive compounds. The impact of extract amount, sonication duration, and temperature on nanoparticle formation was systematically assessed. It was determined that these conditions could ensure efficient extraction while simultaneously ensuring the stability of the extract and the reproducibility of particle formation. The mixture was then allowed to cool to room temperature; it was filtered first through Whatman No. 1 filter paper to obtain a clear aqueous extract. The prepared extract was stored at 4°C in clean containers and used as the reducing and stabilizing agent for nanoparticle synthesis.

Green Synthesis of Iron Oxide Nanoparticles:

Iron Oxide nanoparticles (IONPs) were synthesized via utilizing *P. atlantica* leaf extract, under the influence of two parameters: FeCl_3 concentration and reaction temperature systematically varied (Figure 1). Different molarities of FeCl_3 solutions (0.1, 0.2, 0.3, 0.4, and 0.5 M) were prepared. For each molarity, 100 mL of plant extract was mixed with 100 mL of the FeCl_3 solution under continuous stirring for about 30 minutes. The reaction temperature was systematically carried out at room temperature of 25, 40, 60, and 80°C for the formation of IONPs. In both conditions, there was an immediate color change from yellowish to dark brown/black, which suggests the onset of nanoparticle formation. The nanoparticles were made to undergo centrifugation at 10,000 rpm for 40 minutes using fixed-angle rotor, washed several times with distilled water and dried at 50°C to gently remove residual water without affecting particle structure, and finally calcined at 200 °C. The dried nanoparticles were then calcined at 200°C for 2 hours in air to induce crystallization of $\alpha\text{-Fe}_2\text{Cl}_3$ while minimizing particle growth. The resulting IONPs were stored in a sealed container for further characterization.

The formation of IONPs was confirmed using characterization techniques of X-ray diffraction (XRD) for crystalline structure, Fourier transform infrared spectroscopy (FTIR) for functional groups, field emission scanning electron microscopy (FESEM) for morphology, energy dispersive spectroscopy (EDS) for elemental composition, and UV–visible spectroscopy (UV–Vis) for optical properties.

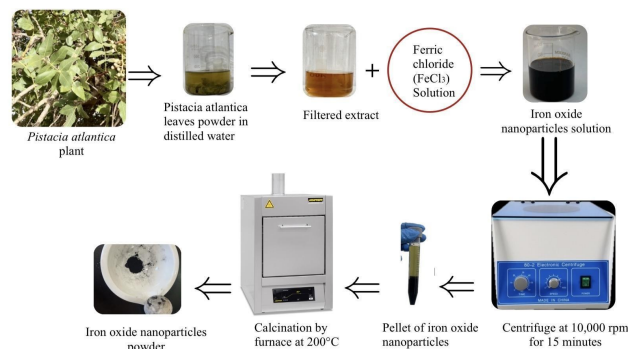


Figure 1: Green Synthesis Process of Iron Oxide Nanoparticles Using *P. atlantica* Leaves Extract and FeCl_3 Precursor.

3. RESULTS AND DISCUSSION

FTIR Analysis:

FTIR analysis was performed to identify the functional groups and bonding involved in the green method and stabilization of $\alpha\text{-Fe}_2\text{Cl}_3$ nanoparticles. The spectrum, recorded in the range of 4000–300 cm^{-1} , showed several peaks, as shown in Figure (2).

Broad absorption bands at 3735.5 and 3415.4 cm^{-1} correspond to O–H stretching vibrations arising from hydroxyl groups of adsorbed water or phenolic/alcoholic groups in *P. atlantica* extract, as confirmed by previous studies (Archana *et al.*, 2021; Lemine *et al.*, 2021). The band at 1629.7 cm^{-1} is attributed to C=C stretching of aromatic rings or H–O–H bending of adsorbed water. In addition, the region at 1522.11, 1308.7, and 913.29 cm^{-1} , associated with C–H bending, indicates the presence of polyphenols, tannins, and flavonoids from the plant extract, thereby confirming the role of phytochemicals as capping agents on the nanoparticle surface. An additional peak at 1146.3 cm^{-1} corresponds to the C–O stretching bond and ether linkages or polysaccharides, supported by literature (Keskin, 2024). Interestingly, strong peaks observed at (614, 542, and 444 cm^{-1}) were characteristic of Fe–O vibrations, confirming the successful formation of iron oxide nanoparticles. This result is in good agreement with the studies reported by Katta (2024).

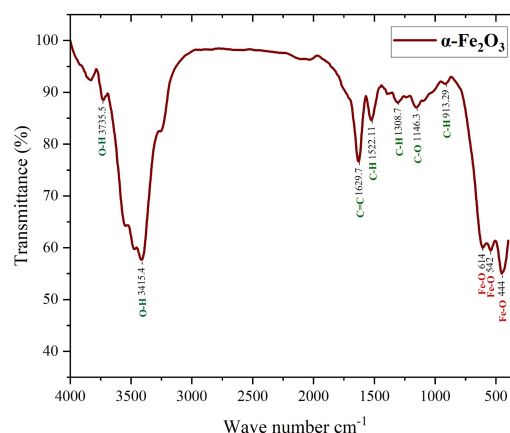


Figure 2: FTIR Transmittance Spectrum of Synthesized $\alpha\text{-Fe}_2\text{Cl}_3$.

These findings identified that *P. atlantica* leaf extract not only acted as a reducing and capping agent but also provided bonding and surface chemistry.

Structural Properties of As-Grown IONPs:

X-ray diffraction (XRD) technique is used to identify the crystalline phases, crystallite size, and structural changes of IONPs synthesized under variations of different conditions (2 precursor and reaction temperature) (Figure 3). The crystalline phase of synthesized IONPs via *P. atlantica* extract was examined under the variation of FeCl_3 concentrations from 0.1 to 0.5M, as illustrated in Figure (3a).

The XRD patterns showed distinct and sharp diffraction peaks of all concentrations at 33.2° (104), 49.5° (024), and 54.1° (116), indicating the formation and crystallinity of $\alpha\text{-Fe}_2\text{Cl}_3$ (hematite) phase. This result is consistent with JCPDS Card No. 33-0664, as reported by Abdullah et al. (2023) and further supported by Umar (2021). The hematite phase was obtained under variation of all concentrations, which exhibits the most stable phase of iron oxide nanoparticles. This study is in good agreement with Archana et al. (2021). According to these observations of the formation of thermodynamically stable hematite nanoparticles, an increment in FeCl_3 concentration while synthesizing IONPs affects the size and crystallinity of nanoparticles. Similarly, Ahmad et al. (2025) found that changing the amount of FeCl_3 affects the crystallinity and size of the particles, but it does not change the type of material, as $\alpha\text{-Fe}_2\text{O}_3$. Higher concentrations (0.3–0.5 M) led to sharper diffraction peaks, indicating better crystallinity and potential growth of the grains, while lower concentrations (0.1–0.2 M) produced wider peaks that suggest smaller Similar trends have been reported in the literature (Fouad, 2019a; Mona et al., 2024).

Classical nucleation theory can explain this behavior. When the concentration of precursors is higher, iron ions are more available, which speeds up nucleation and crystal development. This pattern makes larger crystallites form and causes sharper, more intense XRD peaks. On the other hand, lower concentrations have fewer ions, which slows down growth and makes crystallites smaller. The phase composition stayed the same at all concentrations. These results show that the amount of precursor mainly influences how quickly IONPs form and grow, not their structural phase change (Reindl et al. 2025; Tabasum 2025).

Crystallinity of IONPs under the effect of temperature variation was investigated over a range of $20\text{--}80^\circ\text{C}$, as shown in Figure (3b). The XRD patterns of IONPs presented distinct diffraction peaks at 33.2° (104), 35.6° (110), 49.5° (024), and 54.1° (116) (Hakim, 2023) corresponding to (JCPDS 33-0664). This agreement indicates the formation of a crystalline pure $\alpha\text{-Fe}_2\text{Cl}_3$ phase and a rhombohedrally centered hexagonal structure for all temperatures (Fouad, 2019b). The synthesis of IONPs at room temperature 25°C showed broad diffraction peaks and lower intensities. Increasing the temperature up to 40°C led to removing organic capping around nanoparticles and pro-

viding better crystallinity, which is reflected in sharper peaks and the appearance of a minor peak around 35.6° in XRD (Khanam et al., 2024). As temperature rises to 80°C , it shows enhanced crystallinity and grain growth without undergoing phase transition. Similar findings have been reported, where moderate heating promotes lattice reorganization and enhances crystalline quality in iron oxide nanoparticles (Mona et al., 2024).

Importantly, no transformation phases such as $\gamma\text{-Fe}_2\text{Cl}_3$ or Fe_3O_4 were detected, indicating that the phase composition remains stable and pure with variation in precursor and temperature during synthesis.

Morphological Analysis:

Field Emission Scanning Electron Microscopy (FESEM) technique uses a focused electron beam that analyzes the surface morphology, size distribution, shape, and agglomeration for providing high resolution on the state of Fe_2Cl_3 nanoparticles.

Morphological Analysis of $\alpha\text{-Fe}_2\text{Cl}_3$ Formed at Different FeCl_3 Concentrations:

IONPs were synthesized via *P. atlantica* leaf extract under the different concentrations of FeCl_3 precursor at room temperature, leading to a change in nanoparticle growth and nucleation. Increasing the concentration of FeCl_3 and the amount of free Fe^{3+} ions in the solution leads to more supersaturation and quicker growth of the nanoparticles. FESEM images of nanoparticles synthesized under varying FeCl_3 molarity (0.1–0.5M) are shown in Figure (4a–e).

Average size distributions were conducted with FESEM images using ImageJ software. Determination was done on each molarity as it is clear in Figure (4a–e). At lower concentrations of FeCl_3 precursor (0.1–0.2 M), the average size distribution of IONPs is 31.62 ± 1.48 to 33.61 ± 1.21 . Because of the limited availability of free Fe^{3+} ions, it results in lower nucleation and strong capping of extract phytochemicals, and faster growth leads to the formation of small nuclei with smaller nanoparticles. With the rising molarity of FeCl_3 (0.3–0.5 M), the increased availability of Fe^{3+} ions in solution promoted higher nucleation, as confirmed by Akintelu et al. (2021), resulting in larger nanoparticles with sizes up to 97.14 ± 10.47 nm. It has been noted that higher concentrations led to the creation of bigger nanoparticles, as shown in the FESEM images (Figure 4c–e). It has been reported that because of insufficient capping by phenolic compounds of *P. atlantica* extract in solution, particles are likely to stick together, leading to the formation of larger nanoparticles in size due to the high molarity of the precursor (Whitehead et al., 2021). And following the (Ostwald ripening) model, it stated that increasing molarity increases supersaturation and forms many small nuclei. In good agreement with Akintelu et al. (2021), the instability of the system causes small nanoparticles to undergo diffusion and dissolve in the solution, and their material moves to larger particles, making them grow in size.

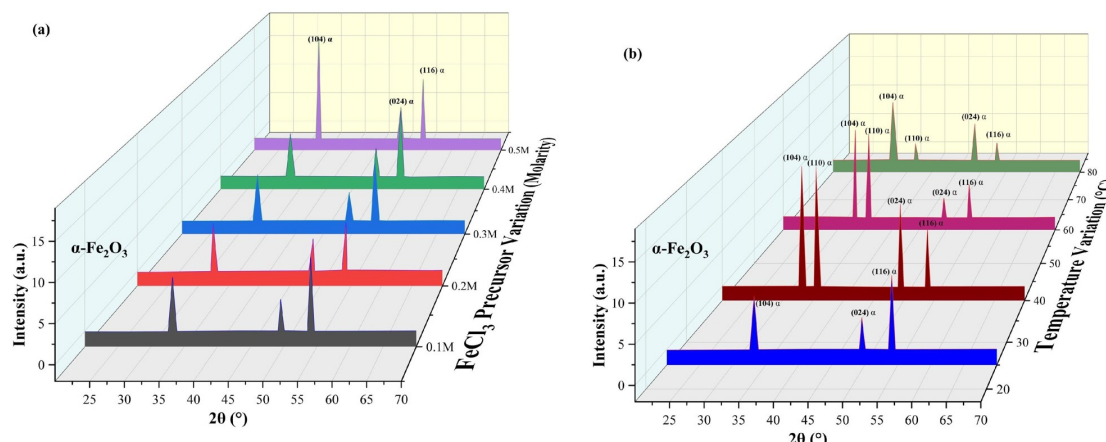


Figure 3: Crystallinity of Iron Oxide Nanoparticles $\alpha\text{-Fe}_2\text{Cl}_3$ under the Effect of (a) FeCl_3 Precursor Varied Concentration of 0.1–0.5M and (b) Temperature Variation of $25\text{--}80^\circ\text{C}$.

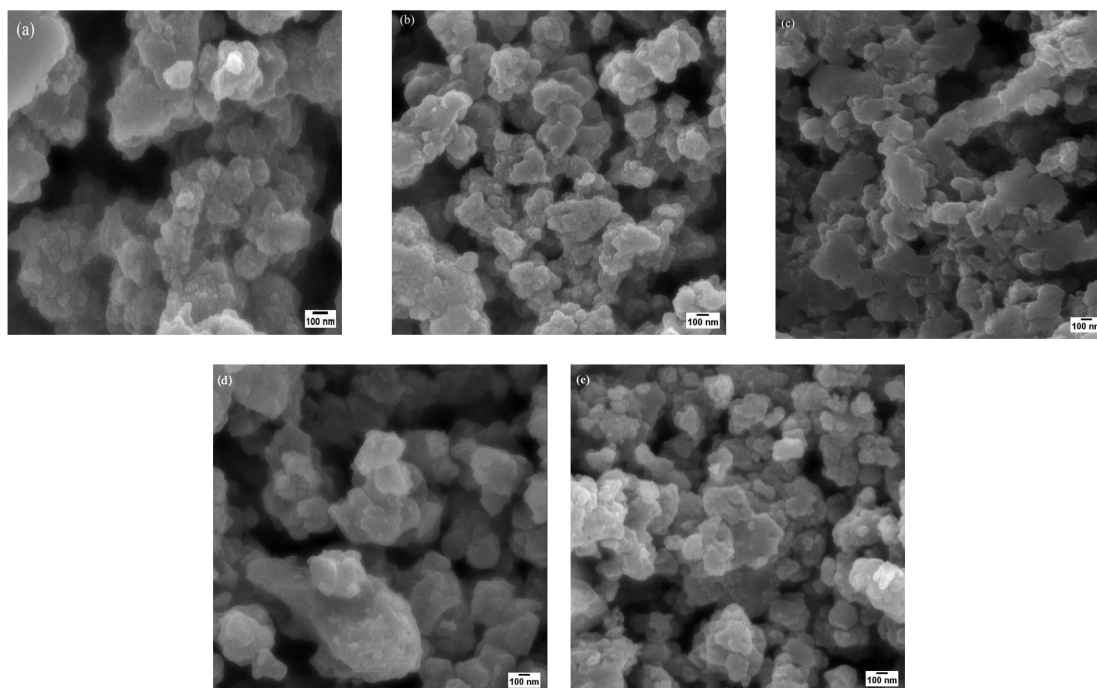


Figure 4: FESEM image of $\alpha\text{-Fe}_2\text{Cl}_3$ nanoparticles synthesized at (a) 0.1M, (b) 0.2M, (c) 0.3M, (d) 0.4M, and (e) 0.5M.

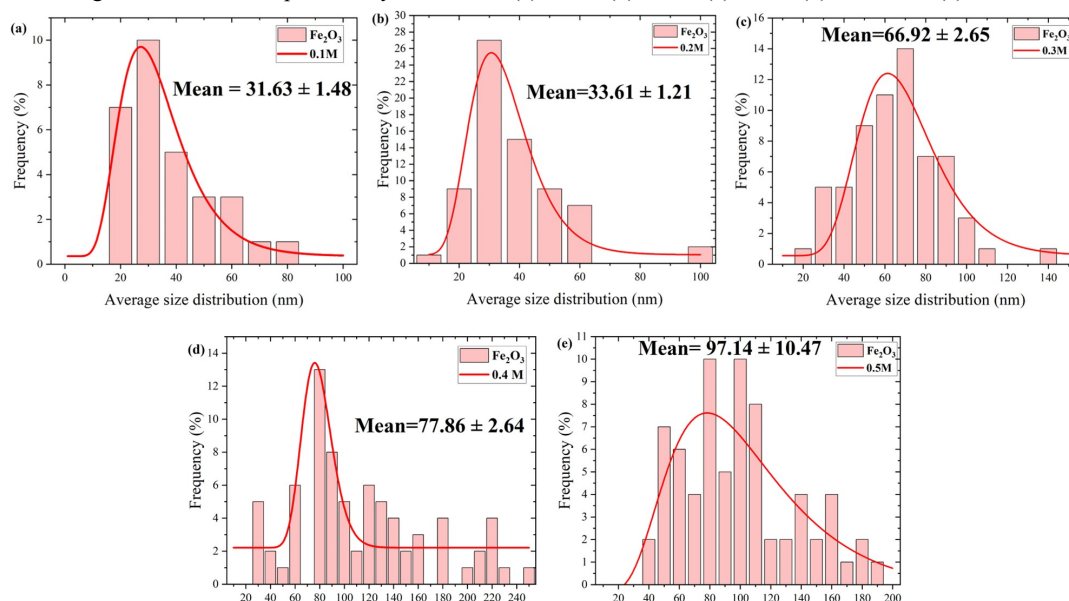


Figure 5: Average size distribution of $\alpha\text{-Fe}_2\text{Cl}_3$ nanoparticles at (a) 0.1M, (b) 0.2M, (c) 0.3M, (d) 0.4M, and (e) 0.5M.

FESEM Characterization of Iron Nanostructures Formed at Controlled Temperatures:

Synthesizing IONPs using *P. atlantica* extract in an eco-friendly way under the effect of temperature has been analyzed. In this study, $\alpha\text{-Fe}_2\text{Cl}_3$ was formed using temperature variation systematically (25°C, 40°C, 60°C, and 80°C). To analyze the morphology of the nanoparticles with temperature variations, the FESEM technique has been employed, as depicted in Figure (6 a-d).

Variation in temperature during synthesizing nanoparticles plays a crucial role in their formation, growth, and aggregation (Jameel *et al.*, 2020). In this research, the influence of changing temperature from room temperature (25 °C to 80°C) was analyzed by using a log-normal model. The findings demonstrated that a rise in temperature results in an increase in nanoparticle size.

Synthesizing IONPs at room temperature, it initiated to reduce Fe^{3+} ions at a low rate due to limited thermal energy. This slow reaction causes growth of smaller nanoparticles in size of 66.92 ± 2.65 nm and poor crystallinity with irregular surface morphologies.

Systematically increasing the temperature from 25 °C to 40 °C improved the kinetic energy of particles slightly and caused better nucleation by forming larger-sized nanoparticles with a mean size of 85.25 ± 3.02 nm. But still this temperature is not sufficient for synthesizing a better crystalline form. Rising temperature, up to 60 °C, resulted in a larger size of IONPs of 138.28 ± 9.3 in their average distribution. At the highest temperature of 80 °C during synthesizing nanoparticles, nanoparticle size increases further to 151.00 ± 8.27 nm. This increase in size might be due to growth over nucleation and enhancing crystalline IONPs.

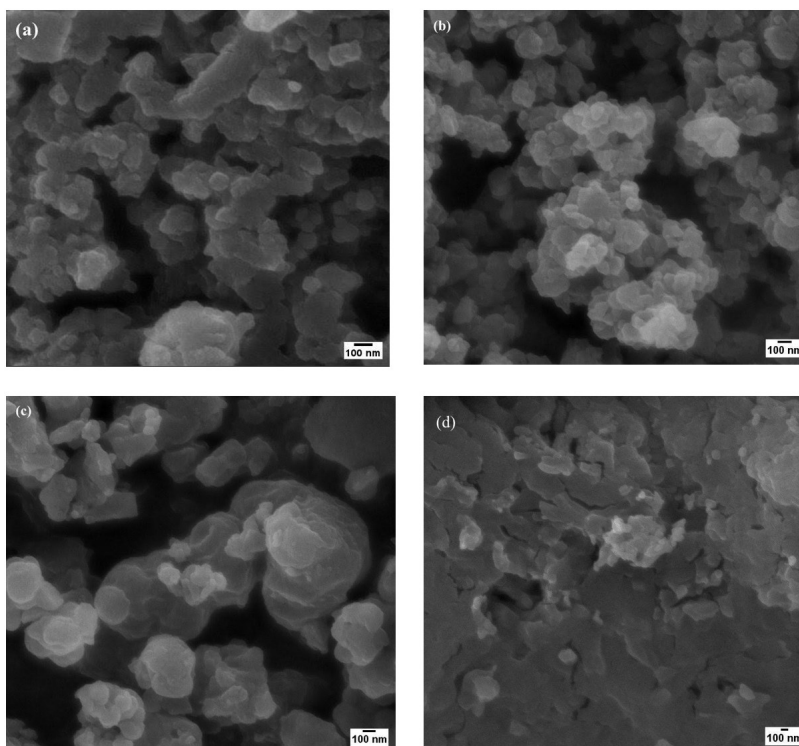


Figure 6: FESEM images of $\alpha\text{-Fe}_2\text{Cl}_3$ nanoparticles synthesized at (a) 25°C, (b) 40°C, (c) 60°C, and (d) 80°C.

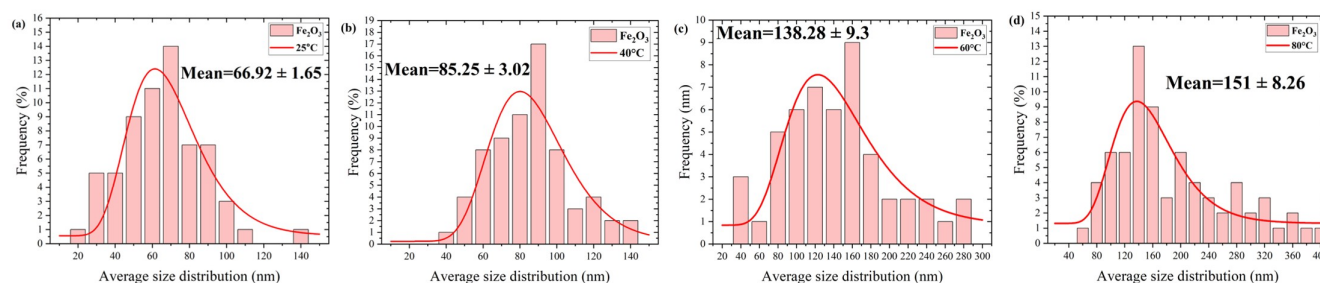


Figure 7: Particles' Average Size Distribution and the Influence of Temperature on $\alpha\text{-Fe}_2\text{Cl}_3$ Nanoparticles (a) 25°C, (b) 40°C, (c) 60°C, and (d) 80°C.

According to the Ostwald ripening model for IONP synthesis, lower temperatures lead to the formation of nanoparticles with a wide range of sizes. In contrast, at 80 °C the system becomes more thermodynamically stable, and the reduction of Fe^{3+} ions is more favorable and highly efficient, resulting in fewer nucleation events but the growth of larger nanoparticles. Ostwald ripening occurs through the diffusive transfer of material from smaller, less stable particles to larger, more stable ones, since larger particles are thermodynamically favored. Higher temperatures further enhance this process by affecting interfacial energy, growth-rate coefficients, and solubility, leading to more pronounced particle growth, in agreement with reported literature. These findings agree with the literature (Flores-Cano, 2022; Shaba *et al.*, 2021).

These observations demonstrate that synthesis temperature critically dictates the physicochemical properties of green-synthesized IONPs. While room temperature and mild heating (25–40 °C) produce smaller but less crystalline nanoparticles, intermediate temperatures (60 °C) enhance both particle growth and partial crystallinity. Excessive heating (80 °C), however, promotes aggregation and broadens growth mechanisms, which may compromise the uniformity and predictability of the nanoparticle system. Therefore, optimizing synthesis temperature is essential for tailoring IONPs for specific appli-

cations in catalysis, biomedicine, or sensing.

EDS Analysis:

Energy-dispersive X-ray (EDS) analysis confirmed that the synthesized nanoparticles contained only Fe and O elements. The measurements were performed at an accelerating voltage of 15 kV, consistent with the findings reported by Hossain (2022a). The EDS spectra of the nanoparticles exhibited sharp peaks between 6.5 and 7 keV, related to Fe K β lines, and the oxygen 0.5 keV peak further indicated the formation of IONPs. These findings are well comparable with the study of al-Akhras *et al.* (2024). In the EDS spectrum, the elemental composition of atomic percentage of Fe was 44.8 at.% and 55.2 at.% of O experimentally have been analyzed and were comparable with theoretical percentages as depicted in (Figure 8). Our results are in close value with the findings of Bristy Biswas (2024), Hossain (2022b) and Rajan (2022).

Optical Properties of IONPs:

Formation and stability of $\alpha\text{-Fe}_2\text{Cl}_3$ in sterile distilled water is confirmed using a UV-vis spectrophotometer in a range of wavelengths from 200 to 900 nm under different parameters.

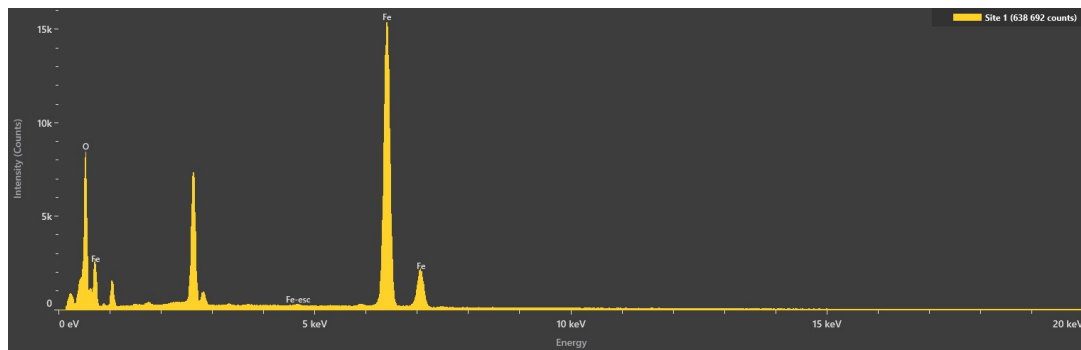


Figure 8: Particles' Average Size Distribution and the Influence of Temperature on α -Fe₂Cl₃ Nanoparticles (a) 25°C, (b) 40°C, (c) 60°C, and (d) 80°C.

UV-Vis Spectra of Fe₂Cl₃ at Varying FeCl₃ Concentrations:

Synthesized Fe₂Cl₃ at different FeCl₃ molarities in between (0.1–0.5 M) were analyzed via the UV–Vis spectra technique (Figure 9). Experimentally, by changing the concentration of FeCl₃ precursor under the same concentration of *P. atlantica* extract, different absorption peaks around (235, 320, 400, 598 nm) were observed at all concentrations. While increasing the concentration from lower molarity to higher it resulted in the formation of larger nanoparticles in size, consistent with the Beer-Lambert law and in good agreement with Quevedo et al. (2021).

A sharp absorption peak was observed at around 235 nm, which is attributed to π - π^* electronic transitions. Confirmed by Shahcheragh et al. (2023), this finding agrees with previous studies of compounds that contain azomethine and phenolic functional groups, such as SALPHEN. This peak appeared at all concentrations, which is attributed to ligand-to-metal charge transfer (LMCT) of electrons transferred from O²⁻ to Fe³⁺ ions. This study is consistent with other studies conducted by Chábera (2021) and Hernández (2024). Another distinct peak appeared at 320 nm, which corresponds to the interaction of phenolic and flavonoid compounds in the *P. atlantica* extract with Fe³⁺ ions and causes electronic transition. This peak indicates the initiation of Fe–O bond. Furthermore, a noticeable shoulder appearing in the region between the 370–450 nm range is observed. To further confirm the formation of nanoparticles, the UV-Vis region was used to measure the absorption band at 300–500 nm. The shoulder at 400 nm originates due to Fe–O transition processes and confirms the formation of iron oxide nanoparticles (Archana et al., 2021; Essawy et al., 2024; Mtibe, 2018). The observed rise in absorption within the specified range is ascribed to the surface plasmon resonance (SPR) of the α -Fe₂O₃NPs, indicating the generation of α -Fe₂O₃NPs (Ashrafi-

Saiedlou, 2025). In the region between 550–700 nm, as shown in Figure (9b), a distinct peak appeared. This peak is attributed to the defect states and oxygen vacancies within the bandgap energy, allowing sub-bandgap transitions. AS supported by Liu et al. (2025), a slight shift of absorption is observed at varied concentrations in region 550–700 nm. This shifting indicates the changing in nanoparticle size and local electronic structure (Reddy, 2020). Literature reports that these defect states are significant because they influence the electronic and optical properties of α -Fe₂Cl₃ nanoparticles, such as charge carrier distribution and light absorption, which are crucial for enhancing functional performance in applications like photocatalysis and other semiconductor-based reactions (Sakamoto, 2024).

The optical band gap (E_g) of the iron oxide nanoparticles (α -Fe₂Cl₃), synthesized using *P. atlantica* extract at varied molarities (0.1–0.5 M), was determined from Tauc plots (equation 1) derived from UV-Vis absorption data, as shown in Figure 10.

$$(\alpha h\nu)^{1/2} = A(h\nu - E_g) \quad (1)$$

This equation was originally proposed by (Tauc et al., 1966).

The shoulder at 400 nm was used to estimate the indirect band gap energies of each α -Fe₂Cl₃ concentration, calculated from Tauc plots using UV-Vis absorption data, as determined by extending the linear portion of each curve to the energy axis. Yielding values of 2.54 eV (0.1 M), 2.40 eV (0.2 M), 2.37 eV (0.3 M), 2.35 eV (0.4 M), and 2.30 eV (0.5 M), it was observed that there was a gradual decrease in bandgap as the molarity of FeCl₃ increased. This tuning in bandgap energies indicates that higher Fe³⁺ levels create defect states or improve interaction of charge carriers. And this tunability makes materials useful for photocatalysis. This trend follows a study by Tahir (2023).

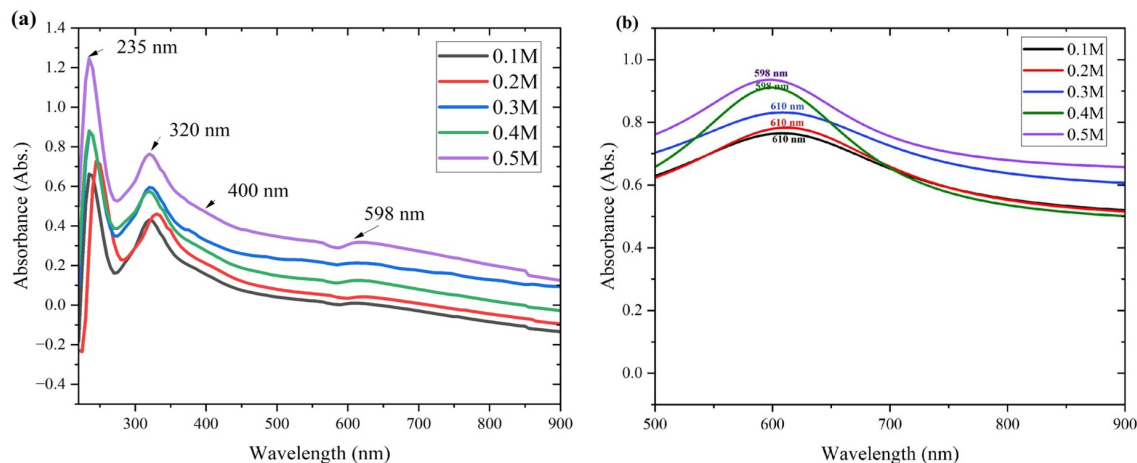


Figure 9: UV–Vis Spectral Analysis of Fe₂Cl₃ (a) at different concentrations of FeCl₃ 0.1 M, 0.2 M, 0.3 M, 0.4 M, and 0.5 M and (b) Absorption Peaks (500–700 nm) Attributed to Defect States.

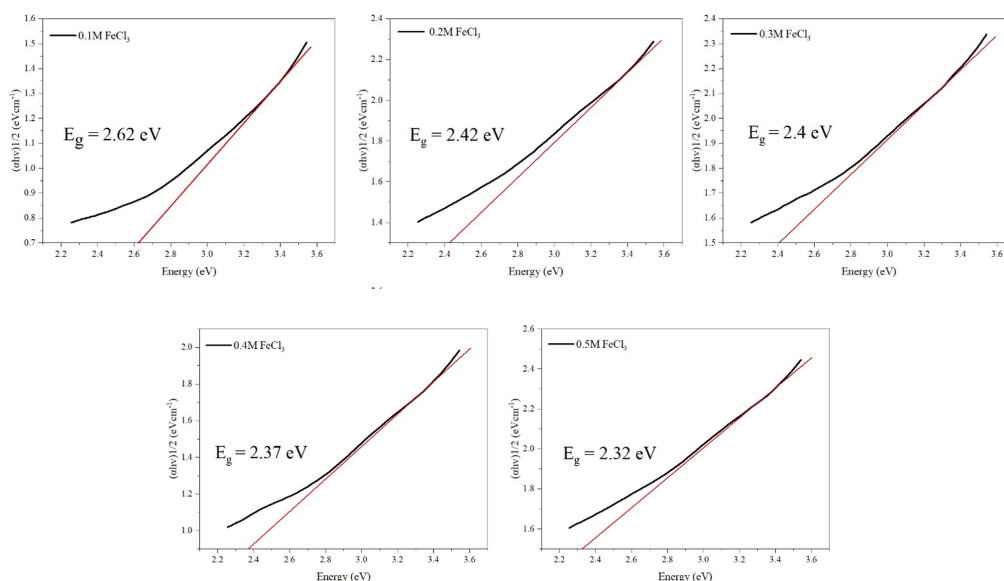


Figure 10: Tauc plots ($(ah\nu)^{1/2}$ versus photon energy ($h\nu$)) of α - Fe_2Cl_3 nanoparticles synthesized using Pistacia leaf extract at FeCl_3 concentrations of 0.1 M, 0.2 M, 0.3 M, 0.4 M, and 0.5 M.

The findings indicate that lower FeCl_3 molarity leads to the formation of smaller nanoparticles with a wider band gap, whereas higher molarities produce larger nanoparticles with a narrower band gap.

UV-Vis Spectra of α - Fe_2Cl_3 at Varying Temperatures:

Fe^{3+} ions are typical in transition of metal oxides (Chábera, 2021; Hernández, 2024). Notably, a strong absorption feature appears around 550–700 nm. This absorption corresponds to the defect states and oxygen vacancies as confirmed by Reddy (2020), although a slight shift occurred from (638 to 615 nm within the changing temperature systematically from (25 - 80 °C). This variation highlights adjustments in the defect state in the bandgap energy as literature confirmed by photoluminescence (PL).

The optical properties of the synthesized nanoparticles were investigated using UV-vis spectroscopy across a range of synthesis temperatures (25 °C, 40 °C, 60 °C, and 80 °C) (Figure 12). All synthesized samples of Fe_2O_3 NPs showed absorption peaks of (237, 319, 400, and 615 nm) under optimized temperatures for studying their optical properties.

The optical properties of IONPs contributed to analyzing structural and electronic properties with increasing temperature. A sharp absorption peak at 237 nm appeared, which is related to the residual organic compound transition of $\pi \rightarrow \pi^*$. Another distinct peak appeared, corresponding to ligand-to-metal charge transfer (LMCT)

transitions, specifically from O^{2-} to Fe^{3+} , as confirmed by Reddy (2020)

The optical band gap (E_g) values of the synthesized nanoparticles were estimated using Tauc plots derived from equation (1) based on their UV-Vis absorption spectra (Figure 13). The region at 400 nm shoulder corresponds to the optical bandgap; increasing temperature leads to a slight shifting, which reflects the variation in particles' optical properties. The band gap energies exhibit an indirect bandgap but consistent diminution bandgap (2.37, 2.32, 2.29, 2.26 eV) with rising synthesis temperatures (25, 40, 60, and 80 °C).

These findings show that when temperature increases, the size of nanoparticles increases and narrows the bandgap energy, causing a slight shifting in absorption edges.

The observed optical behavior of the α - Fe_2Cl_3 nanoparticles can be directly linked with their structural and morphological features.

FESEM data show that changing the concentration of FeCl_3 and the reaction temperature changes the size and shape of the IONPs. This causes the size-dependent bandgap modulation seen in UV-Vis spectra. Smaller particles have broader bandgaps, and larger particles have narrower bandgaps. The absorption feature in the 550–700 nm range is also due to defect-related states, especially oxygen vacancies. These states offer sub-bandgap energy levels, facilitating the absorption of light. These data show a clear link between morphology, faults, and band structure.

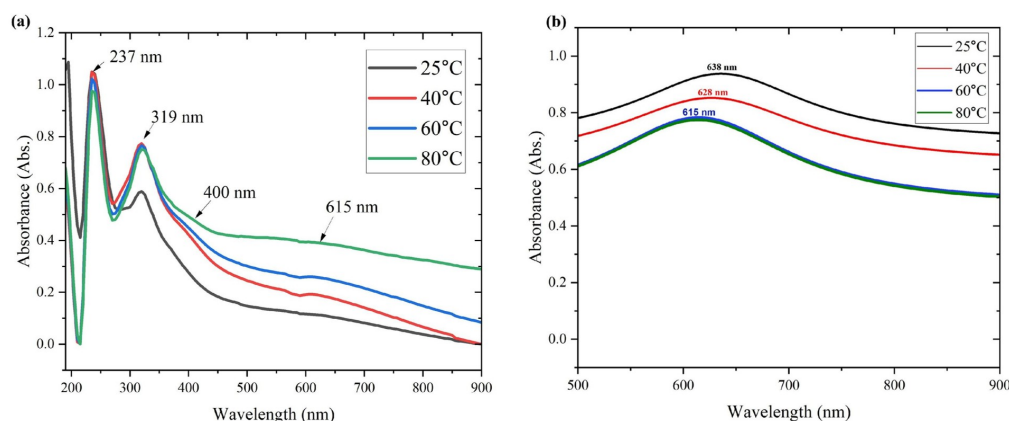


Figure 11: UV-Vis Absorption Spectra of α - Fe_2Cl_3 (a) at different temperatures (25 °C, 40 °C, 60 °C, and 80 °C), and (b) Absorption Peaks (500–900 nm) Attributed to Defect States.

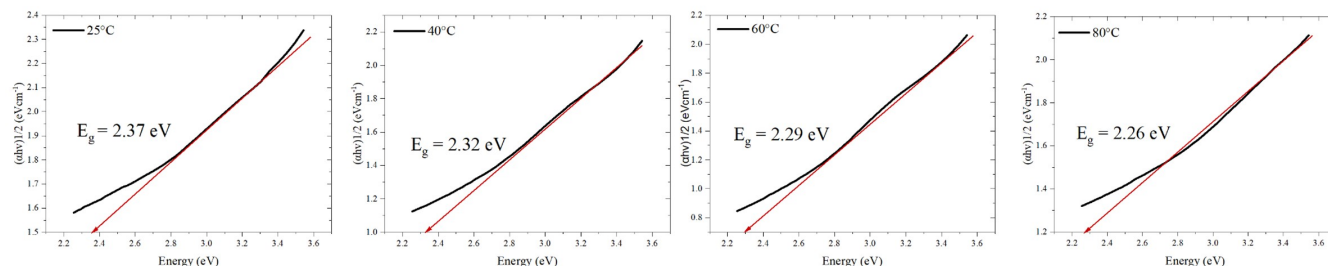


Figure 12: Tauc plots $(\alpha h\nu)^{1/2}$ versus photon energy $(h\nu)$ of α -Fe₂Cl₃ nanoparticles synthesized using Pistacia leaf extract at different temperatures..

4. CONCLUSION

This study clearly showed that pure hematite (α -Fe₂Cl₃) nanoparticles were synthesized using an environmentally friendly method with *P. atlantica* extract. Variations in the concentration of the starting materials and the process temperature had a significant impact on the size, shape, and quality of the particles. Using lower FeCl₃ amounts and mild temperatures led to smaller nanoparticles with wider band gaps. Higher amounts of FeCl₃ and increased temperatures allowed the nanoparticles to grow to a larger size, exhibiting narrower bandgaps. Furthermore, elevated temperatures enhanced crystallinity by eliminating remaining organic compounds. This study showed that carefully adjusting the amount of starting materials and temperature allows for precise changes in the structure and optical properties of α -Fe₂Cl₃ nanoparticles, which might have potential in areas like catalysis, cleaning the environment, and medicine.

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Ethical Statment:

This study did not involve human participants or experimental animals. Plant materials were collected in accordance with local regulations.

Conflict of Interests:

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Author Contributions:

G. H. S. conducted the research, analyzed the data, and prepared the manuscript. O. S. O. supervised the study, conceptualization, data analysis and reviewed the manuscript.

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