

Eco-Friendly Synthesis of Fe₂O₃ Nanoparticles using *Terminalia mantaly* Leaf Extract: Characterization and Applications

B. LAVANYA^{1,2,*} and Y. APARNA¹

¹Department of Physics, Jawaharlal Nehru Technological University, Hyderabad-500085, India

²Department of Physics, Anurag University, Hyderabad-500088, India

*Corresponding author: E-mail: lavanyabandari1@gmail.com

Received: 9 June 2026

Accepted: 17 August 2026

Published online: 9 October 2026

AJC-22483

The present study reports the synthesis of Fe₂O₃ nanoparticles by an eco-friendly method using *Terminalia mantaly* leaf extract. This plant extract contains phytochemicals that act as reducing and stabilising agents during nanoparticle formation, without the use of any harmful chemicals. XRD, FESEM, UV-Vis and PL characterization techniques were employed for the synthesized nanoparticles. XRD analysis confirmed the crystalline nature of the synthesized Fe₂O₃ nanoparticles, with a crystallite size of 18.54 nm. FESEM images revealed predominantly spherical to slightly irregular nanoparticles with rough, textured surfaces and the mean particle size was calculated as 16 nm from the particle-size histogram. UV-Vis spectroscopy was used to evaluate the optical properties and the band gap was estimated to be 2.28 eV using the Tauc plot. PL analysis provided information on charge-carrier recombination and defect states within the material. Photocatalytic experiments using methylene blue showed 85% dye degradation. Antibacterial tests against different bacterial strains showed a concentration-dependent increase in the zone of inhibition, reaching up to 10 mm. The physico-chemical characteristics and functional performance of the Fe₂O₃ nanoparticles support their potential use in environmental remediation and antimicrobial applications, particularly for wastewater treatment and bacterial control.

Keywords: Fe₂O₃ nanoparticles, XRD, *Terminalia mantaly*, Photocatalytic activity, Antibacterial activity.

INTRODUCTION

Advances in nanoscience and nanotechnology have expanded their applications across healthcare, environmental remediation, catalysis and materials engineering. Metal oxide nanoparticles have attracted considerable interest owing to their distinctive optical, magnetic and electrical properties. Semiconductor metal oxides such as TiO₂, ZnO, SnO₂ and Fe₂O₃ possess suitable band structures and high photosensitivity, making them widely investigated as photocatalysts for the degradation of organic pollutants and microbial inactivation [1].

The phase composition, microstructure and physico-chemical characteristics of nanoparticles strongly influence their functional properties and performance. Iron oxide nanoparticles, in particular, have received considerable attention owing to their magnetic, electrical and catalytic properties. Various synthesis routes have been developed, including coprecipitation, sol-gel, hydrothermal and related chemical methods [2-4]. Despite their effectiveness, conventional syn-

thesis approaches may involve hazardous reagents, multiple processing steps, prolonged reaction times and relatively high costs. These limitations have encouraged research into simpler, more economical and environmentally benign synthesis strategies for iron oxide nanoparticles.

In addition, these nanoparticles lose their reactivity when synthesized physically or chemically due to clustering, magnetic properties and their dispersed state upon exposure to air. Toxic materials, destructive byproducts and contamination from chemical precursors are common components of chemical or physical synthesis processes [5]. Growing environmental and economic concerns have increased interest in simple, cost effective and environmentally benign methods for nanoparticle synthesis. Green synthesis using biological resources like bacteria, fungi, algae and plant extracts, has emerged as an alternative to conventional chemical and physical routes. Plant extracts are particularly attractive as they contain bioactive compounds that can act as reducing, capping and stabilizing agents during nanoparticle formation. Plant-mediated synthesis can reduce the use of hazardous chemicals and offers a relatively simple

and economical approach compared with microorganism-based methods [6,7].

Plant extracts can impart biological functionality to nanoparticles while serving as reducing, capping and stabilising agents. Agricultural residues such as fruit peels, leaves, stems and seeds contain phytochemicals, including flavonoids, phenolics and alkaloids, which can facilitate nanoparticle formation and stabilization. Their use provides a sustainable, cost effective and environmentally benign alternative to conventional synthesis routes [8,9]. In present study, *Terminalia mantaly* leaf extract was employed for the synthesis of Fe₂O₃ nanoparticles using ferric nitrate as the precursor. *Terminalia* species contain diverse phytochemicals and have been traditionally used in the management of various ailments such as cardiovascular disorders, cancer, gastrointestinal disorders and malaria [10,11]. The synthesized Fe₂O₃ nanoparticles were characterized to evaluate their structural, morphological and optical properties, followed by assessment of their photocatalytic and antimicrobial activities.

Although several plant extracts have been explored for the green synthesis of Fe₂O₃ nanoparticles, the choice of bio-precursor is important for controlling nucleation, particle growth, optical properties and functional performance. To the best of our knowledge, the use of *T. mantaly* leaf extract for Fe₂O₃ nanoparticle synthesis has not been previously reported. The polyphenolic and tannin-rich constituents of the extract may influence particle nucleation and growth, potentially contributing to controlled particle size, high crystallinity and suitable optical properties. The resulting nanoparticles were evaluated for their photocatalytic and antibacterial performance and compared with previously reported plant-mediated Fe₂O₃ nanoparticles.

EXPERIMENTAL

Fresh leaves of *Terminalia mantaly* were collected at Anurag University in Hyderabad, India and stored in an air-tight container until required for synthesis. Ferric nitrate nonahydrate (Fe(NO₃)₃·9H₂O) was purchased from Sigma-Aldrich and used as iron precursor without further purification. Ethanol and distilled water were used as solvents for the synthesis of Fe₂O₃ nanoparticles.

Preparation of plant extracts: The collected leaves were thoroughly washed under running tap water to remove adhering dust and impurities, followed by three successive washes with distilled water. The leaves were then air-dried and cut into small pieces. Subsequently, 30 g of leaves was transferred to a 250 mL conical flask containing 150 mL of distilled water. The mixture was heated at 80 °C for 30-40 min under continuous magnetic stirring. After cooling to room temperature, the extract was filtered through Whatman filter paper to remove residual plant material and stored at 4 °C until further use.

Synthesis of iron oxide (Fe₂O₃) nanoparticles: For the synthesis of iron oxide nanoparticles, 40 mL of plant extract was mixed with 4 g of Fe(NO₃)₃·9H₂O in a 100 mL beaker. The mixture was heated at 60 °C for 1 h and 30 min with constant stirring using a magnetic stirrer. A colour change from light yellow to red-brown confirmed the formation of iron oxide nanoparticles. Prior to sample collection, the

mixture was centrifuged three times and washed with ethanol to remove impurities.

Antibacterial activity: The antibacterial activity of the green synthesized Fe₂O₃ nanoparticles was evaluated against two Gram-positive bacteria, *Staphylococcus* and *Bacillus*, and two Gram-negative bacteria, *Escherichia coli* and *Klebsiella*. The assay was performed using the agar well-diffusion method [12]. Nutrient agar was sterilized at 121 °C and 15 psi for 15 min, poured into sterile Petri plates and allowed to solidify. A 100 µL aliquot of each bacterial culture was uniformly spread over the agar surface using a sterile cotton swab. Wells were subsequently prepared using a sterile well borer and 100 µL of the nanoparticle suspension was added to each well. The plates were incubated at 37 °C for 18-24 h, after which the inhibition zones were measured.

Photocatalytic activity: Using methylene blue (MB) as a pollutant, the photocatalytic effectiveness of the green synthesized Fe₂O₃ NPs was evaluated under UV radiation. First, 450 mL of distilled water was mixed with 50 ppm of the dye solution to prepare a stock solution. To achieve sorption-desorption equilibrium, 50 mg of Fe₂O₃ catalyst was added to 50 mL of the dye solution taken from the stock solution. The mixture was then placed in a test tube and agitated in the dark for 30 min. After 30 min, 5 mL of dye solution was removed from the sample and UV-Vis spectroscopy was used to estimate its concentration. Under UV illumination, MB solutions containing the Fe₂O₃ catalyst were continuously stirred. The Fe₂O₃ nanoparticles were separated by centrifuging 5 mL samples at every 30 min intervals. A UV-Vis spectrophotometer was used to analyze the clear supernatant and calculate the decrease in absorbance. The degradation percentage of MB dye was calculated using the following formula [13]:

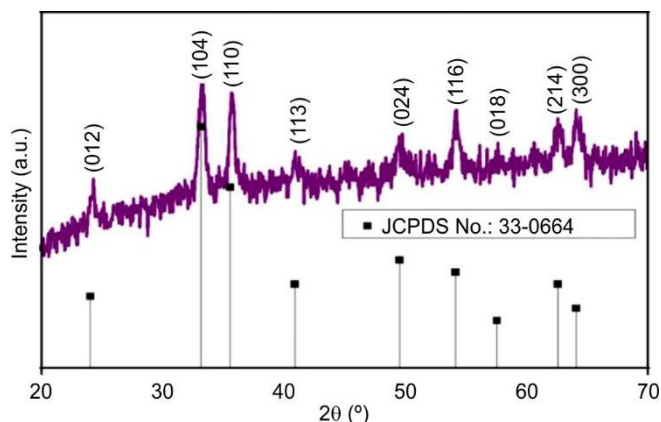
$$D(\%) = \left(\frac{C_i - C_f}{C_i} \right) \times 100$$

where C_i is the dye solution's initial concentration in dark and C_f is the dye mixture's final concentration.

RESULTS AND DISCUSSION

X-ray diffraction (XRD): Fig. 1 shows the XRD pattern of α-Fe₂O₃ synthesized using *T. mantaly* leaf extract. XRD analysis was performed to determine the crystalline phase, phase composition and crystal structure of the synthesized material. Distinct diffraction peaks were observed at 2θ = 24.35°, 33.84°, 36.23°, 41.32°, 49.80°, 54.55°, 57.60°, 63.03° and 64.73°, corresponding to the (012), (104), (110), (113), (024), (116), (018), (214) and (300) planes, respectively. The observed reflections are consistent with the JCPDS card No. 33-0664, which confirm the formation of α-Fe₂O₃ (hematite). The strongest reflection at 2θ = 33.84°, assigned to the (104) plane, which indicates the well-crystalline nature of the synthesized material. The characteristic reflections associated with the (012), (104), (110) and (113) planes are consistent with the rhombohedral structure of hematite [14]. The XRD pattern is in good agreement with reported diffraction characteristics of α-Fe₂O₃.

The broadening of the peaks indicates the nanoscale crystallite size. The crystallite size can be calculated using the

Fig. 1. XRD spectrum of Fe₂O₃ synthesized nanoparticles

Debye-Scherrer equation, given by $D = \frac{k\lambda}{\beta \cos \theta}$. The average

crystallite size is 18.54 nm and is approximately match to the previously reported values [13]. The interplanar distance for the synthesized sample was calculated using formulae

$d = \frac{n\lambda}{\beta \sin \theta}$. The average interplanar distance is 0.2131 nm.

The lattice parameters can be calculated using the equation given by following relation [15]:

$$\frac{1}{d^2} = \frac{4}{3} \left(\frac{h^2 + hk + k^2}{a^2} \right) + \frac{l^2}{c^2}$$

The lattice parameters were determined to be $a = 0.503$ nm and $c = 1.374$ nm, which are in good agreement with the previously reported values [16,17]. These values confirm the rhombohedral crystal structure of hematite (α -Fe₂O₃) and support the successful formation of α -Fe₂O₃ nanoparticles.

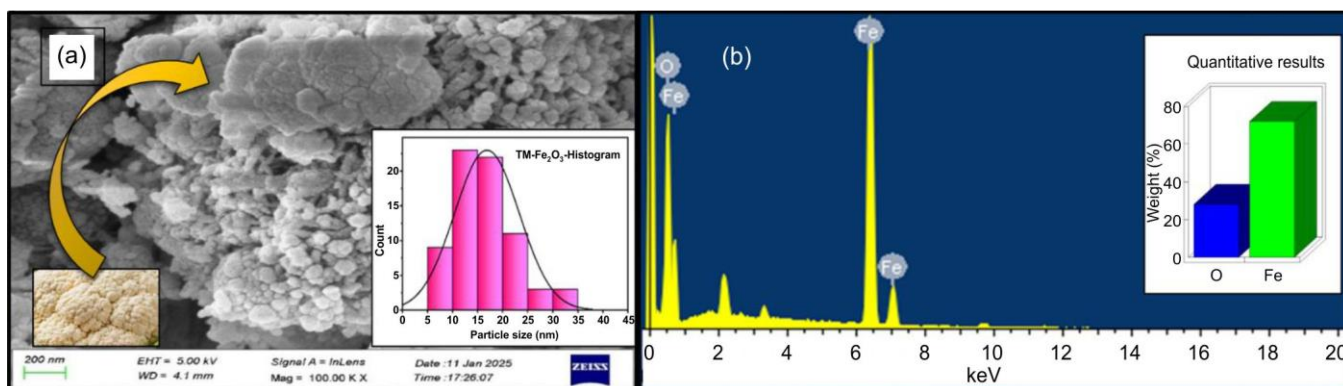
FESEM: The FESEM image (Fig. 2a) reveals highly agglomerated nanoparticles forming irregular, clustered structures. Such agglomeration may arise from strong interparticle interactions, including magnetic dipole interactions and the high surface energy associated with nanoscale particles. The individual nanoparticles exhibit rough, textured surfaces with predominantly spherical to irregular morphologies [18]. The cauliflower-like appearance can be attributed to particle aggregation during synthesis. The average particle size estimated from the FESEM analysis is approximately 16 nm [19]. This

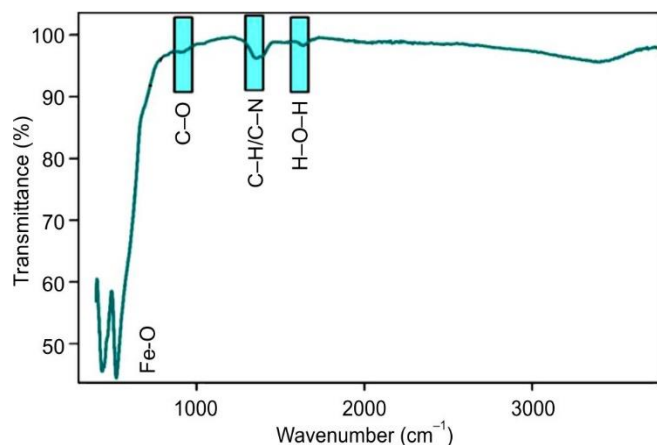
value is comparable to the crystallite size calculated from XRD, which suggest that the observed particles may consist of a small number of crystallites. Such similarity, in isolation, does not establish whether the individual nanoparticles are single-crystalline or polycrystalline. The close correspondence between the FESEM particle size and XRD crystallite size is consistent with the formation of highly crystalline α -Fe₂O₃ nanoparticles, although the presence of grain boundaries within individual particles cannot be excluded.

The EDAX spectrum (Fig. 2b) provides the elemental evidence for the formation of Fe₂O₃ nanoparticles, with key signals corresponding to Fe and O. Minor additional signals may originate from instrumental effects, substrate contributions or trace residual elements from the synthesis process. The measured elemental composition is broadly consistent with the expected Fe–O composition of Fe₂O₃. Thus, the FESEM and EDAX results support the formation of nanoscale Fe₂O₃ with the expected elemental composition and well-defined crystalline characteristics, providing a basis for further evaluation of its photocatalytic and antimicrobial properties.

FTIR studies: As shown in Fig. 3, the FTIR spectrum of the Fe₂O₃ nanoparticles exhibits a prominent absorption band at 532 cm⁻¹, which is assigned to Fe–O stretching vibrations and supports the formation of iron oxide. The absorption region between 700 and 300 cm⁻¹ is characteristic of the metal–oxygen vibrations. The bands associated with plant-derived organic constituents are considerably attenuated, consistent with the thermal decomposition and removal of thermally unstable phytochemicals from the *T. mantaly* extract. The reduction of these organic bands should not be interpreted as direct evidence of increased purity, but rather as evidence of the removal of organic constituents during thermal treatment [18].

The weak absorption bands at 909 and 1412 cm⁻¹ can be assigned to C–O and C–H/C–N stretching vibrations, respectively, which indicate the possible presence of residual organic groups. The band at 1679 cm⁻¹ corresponds to H–O–H bending vibrations of adsorbed water molecules, while the weak band at 3394 cm⁻¹ is associated with O–H stretching vibrations appears from surface hydroxyl groups and/or adsorbed moisture [18]. The dominance of the Fe–O vibration, together with the reduced intensity of organic-related bands is consistent with the formation of Fe₂O₃ nanoparticles. The FTIR findings support the α -Fe₂O₃ phase identified by XRD and the nano-

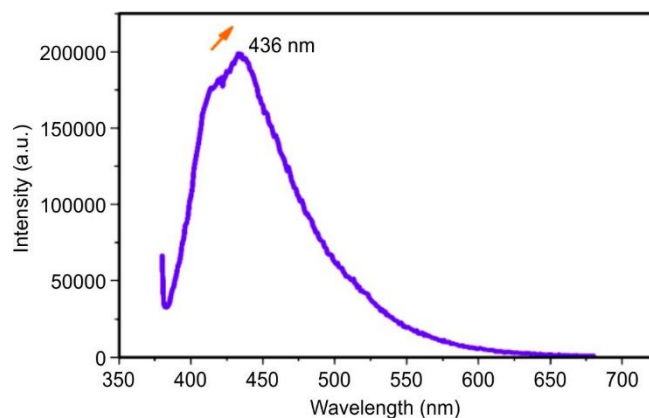
Fig. 2. (a) FESEM image of Fe₂O₃ with histogram and (b) EDAX spectrum with atomic and weight percentage

Fig. 3. FTIR spectrum of Fe₂O₃ synthesized nanoparticles

scale morphology and Fe–O composition observed by FESEM-EDX.

Photoluminescence (PL): The synthesized Fe₂O₃ nanoparticles were subjected to photoluminescence (PL) analysis over the wavelength range of 350–700 nm, as shown in Fig. 4. A broad emission centred at 436 nm is observed in the blue region of the spectrum. This emission can be associated with radiative recombination of photogenerated electron–hole pairs through defect-related states within the band gap. Such states may originate from structural imperfections, surface defects, oxygen vacancies and Fe³⁺/Fe²⁺ centres [19]. The PL intensity provides qualitative information on charge-carrier recombination; higher intensity generally indicates higher radiative recombination, whereas lower intensity is commonly associated with reduced recombination and improved charge separation. Defect states can function as charge-trapping centres and may either promote charge separation or act as recombination sites, depending on their concentration and energetic position.

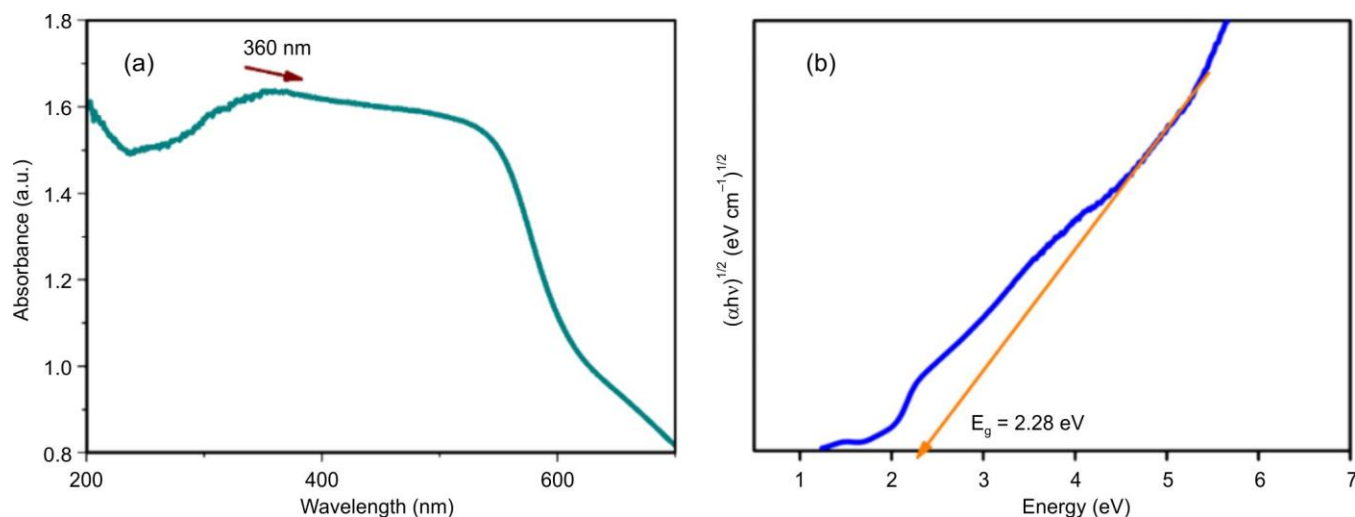
Under UV excitation at 350 nm, electrons are promoted from the valence band to the conduction band, generating electron–hole pairs. The photogenerated carriers can subsequently undergo radiative recombination directly or through defect-related intermediate states within the band gap, result-

Fig. 4. PL spectrum of synthesized Fe₂O₃ synthesized nanoparticles

ing in the PL emission [19]. The broad emission at 436 nm is consistent with the defect-mediated radiative transitions and suggests the presence of structural and/or surface defect states in the synthesized Fe₂O₃ nanoparticles. These defect states can influence charge-carrier dynamics and consequently, the photocatalytic behaviour of the material.

UV-Vis spectroscopy: The UV-visible absorption spectrum of the *T. mantaly* leaf extract mediated-Fe₂O₃ NPs, recorded over the 200–700 nm wavelength range as depicted in Fig. 5a, which show a pronounced absorption band near 360 nm [20]. The observed UV absorption of the synthesized Fe₂O₃ nanoparticles can be associated with ligand-to-metal charge-transfer (LMCT) transitions involving O^{2–} and Fe³⁺ centres. The distinct UV absorption supports the formation of Fe₂O₃ nanoparticles, while the decrease in absorbance in the visible region indicates limited optical absorption at wavelengths above approximately 500 nm. Any shift in the absorption edge may arise from the combined effects of crystallite size, lattice strain, structural defects and surface states associated with the synthesis process.

Although nanoparticle size can influence the optical response of semiconductor materials, the average crystallite size of approximately 16 nm in the present study is considerably larger than the exciton Bohr radius reported for hematite. Strong quantum-confinement effects are consequently unlikely

Fig. 5. (a) UV-Vis absorption spectra of Fe₂O₃ and (b) Tauc plot of synthesized Fe₂O₃ using *Terminalia mantaly* leaf extract

to be the dominant origin of the observed band-gap variation. The optical response is more plausibly associated with defect induced electronic states, lattice distortion and surface-related effects. These features can modify the electronic structure and influence the light-absorption characteristics of the green synthesized Fe₂O₃ nanoparticles.

The optical band gap (E_g) of the synthesized Fe₂O₃ nanoparticles were estimated using the Tauc relation:

$$(\alpha h\nu)^2 = A(h\nu - E_g)$$

Considering that hematite (α -Fe₂O₃) exhibits an indirect fundamental optical transition, the Tauc plot of $(\alpha h\nu)^{1/2}$ versus photon energy ($h\nu$) was employed to estimate the optical band gap. The linear Tauc plot was extrapolated to the photon-energy axis, yielding an optical band-gap energy of 2.28 eV (Fig. 5b). This value is consistent with reported optical band-gap values for hematite and Fe₂O₃ nanostructures, which generally fall within approximately 1.9–2.2 eV, although variations can occur depending on crystallite size, morphology, defects, and measurement conditions [21].

Antibacterial activity: As shown in Fig. 6a–c, the antibacterial response of green synthesized Fe₂O₃ nanoparticles varied with bacterial strain and sample concentration. Against *Staphylococcus*, no inhibition was observed at 25 and 50 μ L, whereas inhibition zones of 7 and 10 mm were recorded at 75 and 100 μ L, respectively. Against *Bacillus*, inhibition zones of 7, 8 and 10 mm were observed at 50, 75 and 100 μ L, respectively,

while no inhibition occurred at 25 μ L [22,23]. The nanoparticles exhibited better activity against *Bacillus* than *Staphylococcus*. However, no measurable inhibition was observed against *E. coli* or *Klebsiella* under the tested conditions. The strain-dependent response may arise from differences in cell-envelope structure and nanoparticle–cell interactions.

Photocatalytic activity: The UV-Vis absorption spectra of the Fe₂O₃ NPs prepared from the *T. mantaly* leaf extracts for the MB dye are shown in Fig. 7a. The graph shows that the strong absorption of MB is correlated with the peak intensity at 660 nm. Degradation of the MB dye was indicated by a gradual decline in absorption peak intensity without a change in the maximum wavelength. The study was carried out in the dark for 30 min prior to the photocatalytic reaction and the degradation percentage was determined to be 0%. As shown in Fig. 7b, the ratio of the starting concentration [$\ln(C_i(C)/C_f(C_0))$] to the MB dye concentration in the *T. mantaly* leaf extract during illumination was plotted against illumination time (t). The graphs demonstrate a linear relationship between $\ln(C/C_0)$ and t and the high correlation coefficient indicates that the catalytic process is consistent with a first-order kinetic model [24,25], which can be expressed as follows:

$$\ln\left(\frac{C}{C_0}\right) = k't$$

where k is the apparent rate constant. The concentration of degradation-causing active sites determines the value of k .

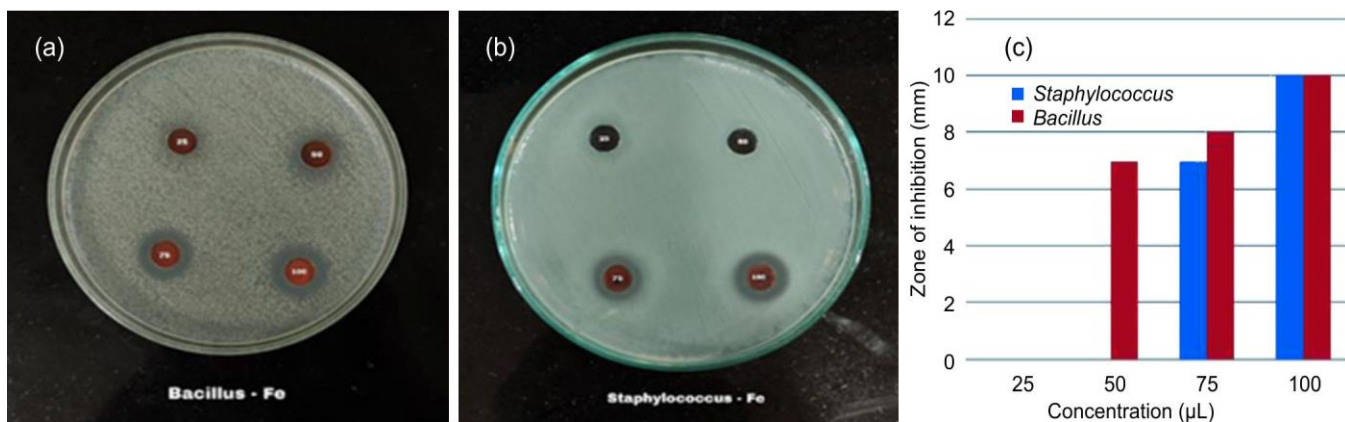


Fig. 6. (a) Zone of inhibition on *Bacillus* bacteria by synthesized Fe₂O₃ nanoparticles, (b) zone of inhibition on *Staphylococcus* bacteria by synthesized Fe₂O₃ nanoparticles and (c) comparison between variation of zone of inhibition of two bacteria

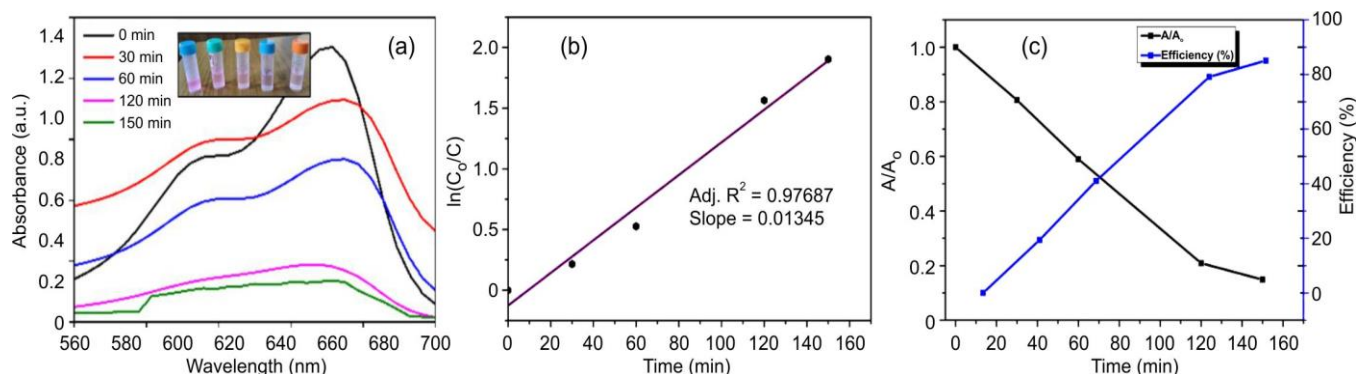


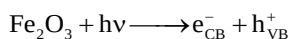
Fig. 7. (a) UV absorption spectra of methylene blue dye, (b) pseudo-first-order kinetic plot of $\ln(C_0/C)$ with irradiation time for MB degradation and (c) variation of absorbance and degradation efficiency with time

The photocatalytic performance of *T. mantaly* leaf extract mediated Fe₂O₃ nanoparticles was assessed by monitoring the degradation of methylene blue dye. In Fig. 7c, the normalized absorbance (A/A₀) decreased steadily with increasing irradiation time, accompanied by a corresponding increase in the degradation efficiency. After 150 min, the degradation efficiency reached approximately 85%, demonstrating effective photocatalytic activity. These results highlight the potential of Fe₂O₃ nanoparticles for wastewater treatment applications.

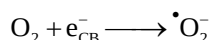
Photocatalytic mechanism: When the sample was exposed to UV light, the electrons were excited from the valence band to the conduction band as the energy exceeds the band gap, generating electrons and holes. These photogenerated electrons reduce oxygen to superoxide radicals O₂^{•−} in the conduction band and holes in the valence band oxidize hydroxide ions (OH[−]) to hydroxyl radicals (OH[•]). These generate reactive oxygen species (ROS) that act on the dye, degrading organic pollutants.

The photocatalytic degradation of methylene blue (MB) using Fe₂O₃ nanoparticles can be represented by the following reactions:

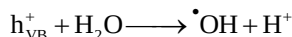
Generation of electron–hole pairs: When Fe₂O₃ absorbs light energy greater than or equal to its band gap:



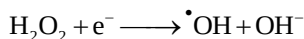
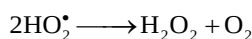
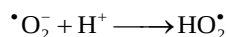
Formation of superoxide radicals:



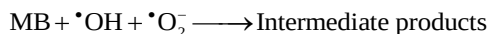
Formation of hydroxyl radicals:



Formation of additional reactive species:



Degradation of methylene blue (MB):



It is postulated that the dominant active radical species and degradation pathways of methylene blue (MB) over the synthesized Fe₂O₃ nanoparticles are provided by the estimated values of VB and CB edge potentials [26,27], using the Mulliken electronegativity concept equations, as follows:

$$E_{\text{VB}} = \chi - E_{\text{e}} + 0.5E_{\text{g}}$$

$$E_{\text{CB}} = E_{\text{VB}} - E_{\text{g}}$$

where χ is the absolute electronegativity of Fe₂O₃ (5.88 eV), E_{e} is the energy of free electrons on the hydrogen scale (≈ 4.50 eV vs. NHE) and E_{g} is the optical band gap (2.28 eV) obtained from the Tauc plot analysis of the experimental data. The calculated values of E_{VB} and E_{CB} edge positions were found at +2.52 V vs. NHE and +0.24 V vs. NHE, respectively. The calculated E_{VB} potential (+2.52 V) is very large and positive compared to the standard potentials for the hydroxyl ion to hydroxyl radical, or for the surface-bound water molecule to hydroxyl radical, reactions (OH[−]/OH[•] = +1.99 V vs. NHE and

H₂O/OH[•] = +2.38 V vs. NHE), respectively. These indicate that photoexcited holes in the valence band have a thermodynamic driving force to oxidize water and/or hydroxyl species to form hydroxyl radicals (OH[•]). The calculated E_{CB} edge (+0.24 V) is less negative than the standard single-electron reduction potential for oxygen (O₂/O₂^{•−} = −0.33 V vs. NHE). Thermodynamically, the direct reduction of dissolved oxygen to form superoxide radical anions (O₂^{•−}) is a poorly favoured reaction. Thus, from an energy perspective of the band structure, direct oxidation of MB by photo-created holes (h⁺) and attack by active hydroxyls (OH[•]) are essentially the dominant mechanisms of photocatalytic degradation of MB over α -Fe₂O₃ while there is minimal contribution from the attack by superoxide radicals [22].

Comparative studies: The comparative data (Table-1) demonstrates that the properties of green-synthesized α -Fe₂O₃ nanoparticles depend strongly on the plant extract employed during synthesis. The reported nanoparticles show noticeable differences in particle size, optical band-gap energy, photocatalytic efficiency, and antibacterial performance. In comparison, the nanoparticles synthesized using *T. mantaly* in the present study exhibit a relatively narrow particle-size range of 14–18 nm with a band-gap energy of 2.28 eV. They also show 85% photocatalytic degradation within 150 min and moderate antibacterial activity with a 10 mm inhibition zone. These findings indicate that *T. mantaly* can serve as an effective biological reducing and stabilizing source for producing α -Fe₂O₃ nanoparticles with useful photocatalytic and antibacterial properties.

Conclusion

In this study, Fe₂O₃ nanoparticles were successfully synthesized using a plant-mediated green synthesis route and characterized by XRD, FESEM, FTIR, PL and UV-Vis spectroscopy. XRD confirmed the formation of crystalline α -Fe₂O₃ with an average crystallite size of approximately 16 nm. FESEM revealed predominantly near-spherical, highly agglomerated nanoparticles with an estimated particle size of about 16 nm. The similarity between the FESEM particle size and XRD crystallite size is consistent with a highly crystalline material, although it does not establish the single- or polycrystalline nature of individual particles. The FTIR band at 532 cm^{−1} was assigned to Fe–O vibrations, supporting the formation of iron oxide, while the remaining weak bands were associated with residual surface functional groups. UV-Vis analysis revealed strong UV absorption, with an estimated optical band gap of approximately 3.5 eV from the Tauc plot. PL analysis indicated the presence of structural and surface defect states that may influence charge-carrier recombination and photocatalytic behaviour. The synthesized Fe₂O₃ nanoparticles exhibited moderate antibacterial and good photocatalytic performance. Antibacterial activity was observed against the tested Gram-positive bacteria, with inhibition zones reaching 10 mm, whereas no measurable activity was observed against the tested Gram-negative strains. The photocatalytic experiments showed approximately 85% degradation of methylene blue within 2 h under the investigated conditions. These findings indicate that plant-mediated Fe₂O₃ nano-

TABLE-1
COMPARISON OF GREEN-SYNTHEZIZED α -Fe₂O₃ NANOPARTICLES USING VARIOUS LEAF EXTRACTS

Plant source (leaf extract)	Particle size (nm)	Band gap (E _g , eV)	Photocatalytic efficiency	Antibacterial performance	Ref.
<i>Musa acuminata</i>	22-32	2.20	90.3% Crystal violet (150 min)	High activity (<i>E. coli</i> & <i>S. aureus</i>)	[8]
<i>Manilkara zapota</i>	25-50	3.58	53.6% Methylene blue (480 min)	Not reported	[28]
<i>Azadirachta indica</i> (Neem)	22-40	2.14	62.0% Methylene blue (120 min)	Active (<i>E. coli</i> , 12 mm; <i>S. aureus</i> , 14 mm)	[29]
<i>Mentha piperita</i> (Peppermint)	17-45	2.25	65% Orange II (180 min)	Active against <i>E. coli</i> (10 mm)	[30]
<i>Acacia nilotica</i>	30-55	2.22	68.0% Methyl orange (150 min)	Zone of inhibition: 11 mm (<i>E. coli</i>)	[31]
<i>Livistona chinensis</i>	12-28	2.16	68% Malachite green (90 min)	Active (<i>B. subtilis</i> , 11 mm; <i>S. aureus</i> , 13 mm)	[32]
<i>Moringa oleifera</i>	20-30	2.09	72% Rhodamine B (180 min)	Moderate inhibition (9 mm)	[33]
<i>Psidium guajava</i> (Guava)	20-45	2.17	75% Congo red (120 min)	Active against <i>S. aureus</i> (13 mm)	[34]
<i>Catharanthus roseus</i>	15-28	2.18	76% Methylene blue (120 min)	Active (<i>E. coli</i> , 13 mm; <i>S. aureus</i> , 15 mm)	[35]
<i>Carica papaya</i>	25-42	2.20	79% Methyl orange (120 min)	Zone of inhibition: 10 mm (<i>E. coli</i>)	[36]
<i>Camellia sinensis</i> (Green tea)	18-35	2.09	81.5% Methylene blue (120 min)	Good activity (<i>E. coli</i> , 12 mm; <i>S. aureus</i> , 14 mm)	[37]
<i>Aloe vera</i>	16-28	2.11	82.5% Rhodamine B (150 min)	Good activity (<i>S. aureus</i> , 15 mm)	[38]
<i>Eucalyptus globulus</i>	10-25	2.10	95% Rhodamine B (340)	Strong activity against bacterial pathogens	[39]
<i>Terminalia mantaly</i>	14-18	2.28	85% (150 min)	Moderate inhibition (10 mm)	Present work

particles have potential for antimicrobial coatings and photocatalytic treatment of dye-contaminated water, subject to further assessment of stability, reusability and performance under real conditions.

ACKNOWLEDGEMENTS

The authors thank the Department of Physics at Anurag University for conducting the Photocatalytic activity tests.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

REFERENCES

- M. Alagiri and S.B.A. Hamid, *J. Mater. Sci. Mater. Electron.*, **25**, 3572 (2014); <https://doi.org/10.1007/s10854-014-2058-0>
- J. Jesus, J. Regadas, B. Costa, J. Carvalho, A. Pádua, C. Henriques, P.I.P. Soares, S. Gavinho, M.A. Valente, M.P.F. Graça and S. Soreto Teixeira, *Pharmaceutics*, **16**, 1578 (2024); <https://doi.org/10.3390/pharmaceutics16121578>
- A. Mansoor and K. Rasheed, *J. Recent Adv. Nanomed. Nanotechnol.*, **1**, 555562 (2025); <https://doi.org/10.19080/JRANN.2025.01.555562>
- M. Farahmandjou and F. Soflaee, *Phys. Chem. Res.*, **3**, 191 (2015); <https://doi.org/10.22036/pcr.2015.9193>
- V.C. Karade, S.B. Parit, V.V. Dawkar, R.S. Devan, R.J. Choudhary, V.V. Kedge, N.V. Pawar, J.H. Kim and A.D. Chougale, *Heliyon*, **5**, e02044 (2019); <https://doi.org/10.1016/j.heliyon.2019.e02044>
- P.C. Nagajyothi, M. Pandurangan, D.H. Kim, T.V.M. Sreekanth and J. Shim, *J. Cluster Sci.*, **28**, 245 (2017); <https://doi.org/10.1007/s10876-016-1082-z>
- S.J. Nadaf, N.R. Jadhav, H.S. Naikwadi, P.L. Savekar, I.D. Sapkal, M.M. Kambli and I.A. Desai, *OpenNano*, **8**, 100076 (2022); <https://doi.org/10.1016/j.onano.2022.100076>
- T. Indhumathi, N. Krishnamoorthy, R. Valarmathy, K. Saraswathi, S. Dilwyn and S. Prabhu, *Nano Biomed. Eng.*, **14**, 254 (2022); <https://doi.org/10.5101/nbe.v14i3.p254-262>
- M.A.S. Chowdhury, M.M. Islam and M. Jamal, *Results Chem.*, **16**, 102328 (2025); <https://doi.org/10.1016/j.rechem.2025.102328>
- X.-R. Zhang, J. S. Kaunda, H.-T. Zhu, D. Wang, C.-R. Yang and Y.-J. Zhang, *Nat. Prod. Bioprospect.*, **9**, 357 (2019); <https://doi.org/10.1007/s13659-019-00222-3>
- M.S. Majoumou, J.R. Sharma, N.R.S. Sibuyi, M.B. Tincho, F.F. Boyom and M. Meyer, *Molecules*, **25**, 4469 (2020); <https://doi.org/10.3390/molecules25194469>
- M.I. Abou-Dobara, M.A. Kamel, A.K.A. El-Sayed and M.M. El-Zahed, *Discov. Appl. Sci.*, **6**, 113 (2024); <https://doi.org/10.1007/s42452-024-05770-z>
- H. Al-Husseini, B.T. Sih and A.M. Al-Araji, *J. Phys.: Conf. Ser.*, **2114**, 012082 (2021); <https://doi.org/10.1088/1742-6596/2114/1/012082>
- M.A. Mubarak, J. Ali, B. Khattak, F. Fozia, T.A. Khan, M. Hussain, M. Aslam, A. Iftikhar and I. Ahmad, *ACS Omega*, **9**, 166 (2024); <https://doi.org/10.1021/acsomega.3c03078>
- M.S. Aida, N. Alonizan, B. Zarrad and M. Hjiri, *J. Taibah Univ. Sci.*, **17**, 2221827 (2023); <https://doi.org/10.1080/16583655.2023.2221827>
- A. Lassoued, M.S. Lassoued, B. Dkhil, S. Ammar and A. Gadri, *Physica E*, **97**, 328 (2018); <https://doi.org/10.1016/j.physe.2017.12.004>
- P. Dhull, R.K. Lohchab, M. Kumari, K. Singh, A.K. Bhankhar and Shaloo, *Nature Environ. Pollut. Technol.*, **23**, 321 (2024); <https://doi.org/10.46488/NEPT.2024.v23i01.027>
- H. Esmaeili, F. Asghartabar Kashi, Z. Moradi Alvand, L. Parseghian, F. Askari and H. Rafati, *Sci. Rep.*, **15**, 42122 (2025); <https://doi.org/10.1038/s41598-025-26129-3>

19. D.H. Hilo, A.H. Ismail and Z.S. Al-Garawi, *Al-Mustansiriyah J. Sci.*, **33**, 64 (2022);
<https://doi.org/10.23851/mjs.v33i4.1208>
20. A. Lassoued, M.S. Lassoued, B. Dkhil, S. Ammar and A. Gadri, *Physica E*, **101**, 212 (2018);
<https://doi.org/10.1016/j.physe.2018.04.009>
21. S. Agarwala, Z.H. Lim, E. Nicholson and G.W. Ho, *Nanoscale*, **4**, 194 (2012);
<https://doi.org/10.1039/C1NR10856E>
22. M.A. Butler and D.S. Ginley, *J. Electrochem. Soc.*, **125**, 228 (1978);
<https://doi.org/10.1149/1.2131419>
23. A. Khalaf, D. Abu-Dalo and E. Alshamaileh, *Scient. World J.*, **2024**, 8644322 (2024);
<https://doi.org/10.1155/2024/8644322>
24. K. Adhikari, K. Chhetri, D. Acharya, B. Pant and A. Adhikari, *Catalysts*, **12**, 1188 (2022);
<https://doi.org/10.3390/catal12101188>
25. M.A. Khan, M. Ahmed, S.H. Abu-Hussien, M.U. Zahid and B.F. Alharbi, *Sci. Rep.*, **15**, 33107 (2025);
<https://doi.org/10.1038/s41598-025-17750-3>
26. T.K. Townsend, E.M. Sabio, N.D. Browning and F.E. Osterloh, *Energy Environ. Sci.*, **4**, 4270 (2011);
<https://doi.org/10.1039/c1ee02110a>
27. M. Sharmila, R.J. Mani, C. Parvathiraja, S.M.A. Kader, M.R. Siddiqui, S.M. Wabaidur, M.A. Islam and W.-C. Lai, *Water*, **14**, 2301 (2022);
<https://doi.org/10.3390/w14152301>
28. S. Sharma, D.K. Yadav, K. Chawla, N. Lal, C. Lal, P. A. Alvi, *Rasayan J. Chem.*, **15**, 2165 (2022);
<https://doi.org/10.31788/RJC.2022.1536988>
29. M.L. Mugas, G. Calvo, J. Marioni, M. Céspedes, F. Martinez, D. Sáenz, G. Di Venosa, J.L. Cabrera, S.N. Montoya and A. Casas, *J. Photochem. Photobiol. B*, **214**, 112089 (2021);
<https://doi.org/10.1016/j.jphotobiol.2020.112089>
30. M.H. Al-Saidi, A.J. Abbas, A.M. Farhan, A.T. Aluaa, Aluaa A. T., *IOP Conf. Ser. Earth Environ. Sci.*, **1567**, 012038 (2025);
<https://doi.org/10.1088/1755-1315/1567/1/012038>
31. E. Da'na, A. Taha and E. Afkar, *Appl. Sci.*, **8**, 1922 (2018);
<https://doi.org/10.3390/app8101922>
32. E. Veg, A. Raza, S. Rai, P. Bansal, S. Sharma, N. Mishra, R. Gupta, S. Mishra, S. Joshi, A.R. Khan and T. Khan, *RSC Sustain.*, **3**, 5609 (2025);
<https://doi.org/10.1039/D5SU00349K>
33. L. Katata-Seru, T. Moremedi, O.S. Aremu and I. Bahadur, *J. Mol. Liq.*, **256**, 296 (2018);
<https://doi.org/10.1016/j.molliq.2017.11.093>
34. A. Kumar, *ICCK Trans. Adv. Funct. Mater. Process*, **1**, 5 (2025);
<https://doi.org/10.62762/TAFMP.2025.843514>
35. J.B. Dulla, L.P. Kanchibotla, C.V. Tirupati, S. Boddu and V.P. Kodali, *J. Biochem. Technol.*, **16**, 24 (2025);
<https://doi.org/10.51847/U7jSlxe2f8>
36. M.S.H. Bhuiyan, M.Y. Miah, S.C. Paul, T.D. Aka, O. Saha, M.M. Rahaman, M. J. I. Sharif, O. Habiba and M. Ashaduzzaman, *Heliyon*, **6**, e04603 (2020);
<https://doi.org/10.1016/j.heliyon.2020.e04603>
37. T. Biswas, S.S.S. Kubra and S. Awasthi, *BioNanoSci.*, **14**, 581 (2024);
<https://doi.org/10.1007/s12668-023-01204-z>
38. A. Priyadharsan, K. Ramar, M. Handayani, G. Gnanamoorthy, M.R. Shaik, T. Kasilingam, B. Shaik and A. Guru, *Water, Air Soil Pollut.*, **235**, 309 (2024);
<https://doi.org/10.1007/s11270-024-07120-6>
39. F. Mahmood, N. Nazeer, M.M. Rekha, K.F. Alsharif, F.M. Alzahrani, K.J. Alzahrani, J. Bansal, H. Imanov, L. Chopra, I. Kaur, S. Eshkaraev, A. Smerat, A. Sanam and M.Z. Sadikan, *Front. Microbiol.*, **17**, 1871774 (2026);
<https://doi.org/10.3389/fmicb.2026.1871774>