

Synthesis and Application of Cellulose–Iron Nanoparticle for Degradation of Methylene Blue Dye Using Photocatalytic UV Reactor

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ABSTRACT

This study presents the green synthesis, fabrication, characterization, and application of a biopolymer-based cellulose–iron nanomembrane for the degradation of pharmaceutical contaminants from water. Iron oxide nanoparticles (Fe_2O_3) were synthesized using *Punica granatum* (pomegranate) peel extract as a natural reducing and stabilizing agent, eliminating the need for toxic chemicals, and were characterized by DLS and FTIR, confirming a uniform particle size of 225.4 nm and the presence of functional groups responsible for nanoparticle formation and stabilization. The synthesised nanoparticle was applied in a UV photocatalytic reactor for the degradation of Methylene Blue Dye, where the combined effects of membrane filtration, adsorption, and UV-induced advanced oxidation processes resulted in efficient pollutant degradation. Experimental results showed that degradation efficiency increased with time, achieving up to 76% degradation within 60 minutes, following pseudo-first-order kinetics, mainly due to the generation of highly reactive hydroxyl radicals ($\bullet\text{OH}$) under UV irradiation. Overall, the study demonstrates that the iron nanoparticle–UV reactor system is an effective, sustainable, and promising solution for pharmaceutical wastewater treatment, contributing to the advancement of green nanotechnology in environmental remediation.

1. INTRODUCTION

This project focuses on the development of an eco-friendly and efficient system for the degradation of Methylene Blue Dye from water using a iron nanoparticle integrated with a UV photocatalytic reactor. In recent years, the presence of antibiotics such as Methylene Blue Dye

in water bodies has become a serious environmental concern due to their persistence, toxicity, and contribution to antibiotic resistance. Conventional treatment methods are often inadequate in completely removing these pollutants, necessitating the development of advanced and sustainable technologies(1).To address this issue, a green synthesis approach was adopted for the preparation of iron nanoparticles using *Punica granatum* (pomegranate) peel extract, which acts as a natural reducing and stabilizing agent. The developed nano particle was extensively characterized using analytical techniques such as FTIR, DLS confirm its structural, chemical, (3).The prepared iron nano particle was then utilized in combination with a UV reactor to study the photocatalytic degradation of Methylene Blue Dye. The system operates through a synergistic mechanism involving adsorption, and UV-induced advanced oxidation processes. This integrated approach enhances the generation of reactive hydroxyl radicals, which play a key role in breaking down

complex Methylene Blue Dye into simpler, less harmful substances(2).

2. MATERIALS AND METHODS

2.1. Preparation Of *Punica granatum* (Pomegranate) Peel

The outer layer of the pomegranate (*Punica granatum*) peel was collected from fresh juice shops near GCT Coimbatore, specifically utilized for its high concentration of beneficial polyphenols and antioxidants (6). The collected peels were thoroughly washed with disinfected water to remove impurities, dried completely to eliminate moisture content and then ground into a fine powder to enhance extraction efficiency(6). For the preparation of the extract, 5g of the pomegranate peel powder were combined with 100ml of disinfected water and boiled for 15 minutes to maximize the extraction of the bioactive compounds. After cooling, the solution was filtered using Whatman filter paper to remove all solids(6). The resulting clear filtrate was then collected and utilized directly as the natural reducing and stabilizing agent necessary for the subsequent nanoparticle synthesis process [6] .

2.2. Synthesis and Purification of Iron Oxide Nanoparticles

Fe₂O₃NPs were synthesized using FeCl₃Salt *Punica granatum* peel extract(7). A 0.05M FeCl₃ solution was added dropwise to the extract under constant stirring. The reduction of Fe³⁺ions was confirmed by a rapid color change from pale yellow to a black precipitate, indicating the formation of iron oxide nanoparticles(7).Post-synthesis,the nanoparticles underwent a rigorous purification using multiple washing cycles with distilled water and absolute ethanol to eliminate unreacted Fe³⁺ions and residual organic compounds(7). The purified Fe₂O₃NPs were then dried in a low-temperature convection oven to maintain stability and stored in airtight containers, confirming their readiness for polymer matrix integration(7).

2.3. Characterization of Nanoparticle Analysis

The physical and chemical properties of The Fe₂O₃ nanoparticles were confirmed using PSA (DLS) to measure the hydrodynamic size and PDI(11) and FTIR to establish chemical composition and surface interactions(12).

3. CHARACTERIZATION OF IRON NANO PARTICLE

3.1. Characterization Of Iron Nanoparticle

Particle Size Analyzer(PSA) was used to determine the particle size distribution and uniformity of the synthesized nanoparticles. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify the functional groups involved in nanoparticle formation.

3.1.1. Particle Size Analyzer(PSA)

The PSA Curve of Iron nano particle was shown in Fig.3.1.The Particle Size Analyzer (PSA) confirmed the synthesis of iron oxide nanoparticles with a Z- average particle size of 225.4 nm, indicating that the particles were within the nanometer range (18). In Fig 3.1. the single sharp peak in the intensity distribution curve showed a monodisperse nature with uniform particle distribution and minimal aggregation. The Polydispersity Index (PDI) value of 0.284 indicated a narrow size distribution and good stability. These outcomes confirm that the synthesized nanoparticles were stable, well- dispersed, homogeneous, It was suitable for incorporation into the cellulose matrix for nanomembrane fabrication.

3.1.2. Fourier Transform Infrared Spectroscopy (FTIR)

As shown in Figure 3.2, Fourier Transform Infrared Spectroscopy analysis of the synthesized iron oxide (Fe_2O_3) nanoparticles confirmed the formation and stabilization of nanoparticles through sustainable synthesis. A strong absorption peak observed at 580.98 cm^{-1} corresponded to Fe–O stretching vibration, indicating the presence of iron oxide bonds (19).

Peak observed at 2518.59 cm^{-1} , Corresponding to the O–H stretching vibration, illustrate the presence of hydroxyl groups (20). Peak detected at 1810.86 cm^{-1} – Assigned to the C=O stretching vibration, representing carbonyl compounds (21). The peak 1478.01 cm^{-1}

Ascribed to C–O stretching, related with alcohol or ester groups (22). The peak 1028.80 cm^{-1} Represents the C–N stretching vibration, confirming the presence of amine or amide groups

(23). The peak 481.32 cm^{-1} Corresponds to the Fe–O vibration, confirming the formation of iron oxide bonds (24). These biomolecules acted as reliable reducing and stabilizing mediators, preventing nanoparticle aggregation (19). Thus, FTIR spectrum validated the formation of Fe–O bonds and confirmed that the synthesized Fe_2O_3 nanoparticles were effectively stabilized by bio-organic compounds, ensuring purity and structural integrity. The functional groups and confirming the specific interaction between the Fe–O bonds sites.

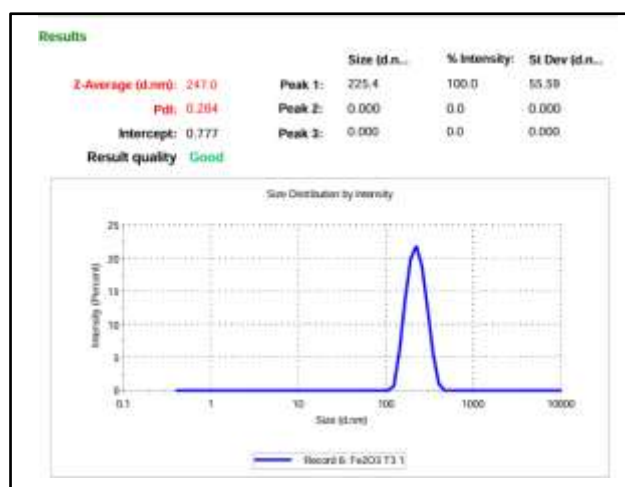


Fig.3.1. PSA Curve of synthesised Iron nano particle

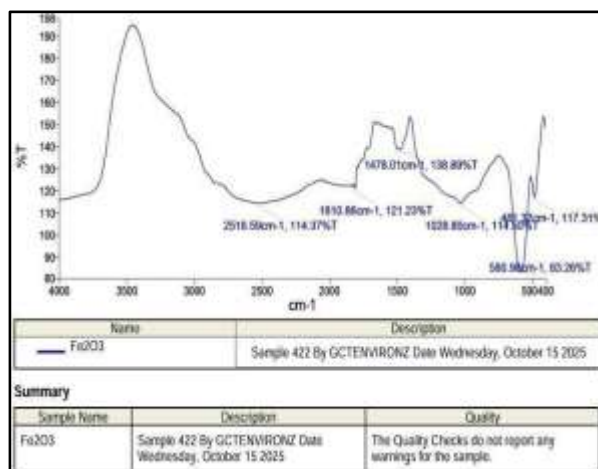


Fig 3.2. FTIR spectrum of synthesized iron nanoparticles showing absorption bands corresponding to functional groups responsible for reduction and stabilization

4. PHARMACEUTICAL DRUG DEGRADATION USING IRON NANO PARTICLE–UV PHOTO CATALYTIC REACTOR

The contamination of water resources by Methylene Blue Dye compounds has emerged as a critical environmental issue in recent years. Antibiotics such as amoxicillin are extensively used in medical and veterinary applications, and a significant fraction of these compounds is discharged into aquatic systems through hospital effluents and industrial wastewater(20). These contaminants are persistent in nature and are not effectively removed by conventional wastewater treatment processes. The presence of pharmaceutical residues in water bodies can lead to serious consequences such as the development of antibiotic-resistant microorganisms, toxicity to aquatic life, and disruption of ecological balance(21). Therefore, the development of efficient and sustainable treatment technologies is essential. In this context, the integration of **iron nano particle with UV reactors** has gained attention as an advanced treatment method. This hybrid system combines membrane filtration, adsorption, and photocatalytic degradation to achieve enhanced degradation efficiency of pharmaceutical pollutants.

4.1. Principle Of Operation

The iron nano particle –UV reactor system operates based on a combined mechanism involving **adsorption, and UV-induced advanced oxidation processes(22)**. The iron nano particle acts as a primary treatment unit, where contaminants are removed through adsorption and size exclusion. The treated water is then subjected to UV irradiation, typically at a wavelength of 254 nm, which facilitates the breakdown of remaining methylene blue dye compounds. Iron nanoparticles present in the membrane or solution enhance the generation of reactive oxygen species, particularly hydroxyl radicals ($\bullet\text{OH}$), which are highly effective in degrading complex organic molecules into simpler and less harmful substances(23).

4.2. Mechanism of methylene blue dye Degradation

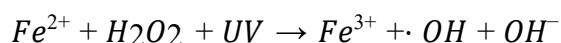
4.2.1. Adsorption

The iron nano particle possesses a high surface area due to the presence of nanoparticles. Methylene blue dye is adsorbed onto the nano particle surface through physical and chemical interactions(32).

4.2.2. UV- Photocatalytic Degradation

Upon exposure to UV radiation, the iron nanoparticles facilitate the generation of reactive radicals. These radicals attack the methylene blue dye and initiate a series of oxidation reactions, leading to their degradation(36).

The simplified reaction mechanism can be expressed as:



The hydroxyl radicals produced are highly reactive and capable of breaking down complex molecular structures present in methylene blue dye compounds.

4.2.3. Experimental Procedure

The experimental procedure for the degradation of methylene blue dye was carried out systematically. Initially, a dye solution of methylene blue dye with a known concentration was prepared(18). The pH of the solution was then adjusted to the desired level to optimize the treatment conditions. The prepared solution was passed through an iron nano particle to degrade bulk contaminants and improve the efficiency of subsequent treatment(20). The filtrate obtained was collected in a UV reactor, where it was exposed to ultraviolet radiation at a wavelength of 254 nm under continuous stirring to ensure uniform treatment. Samples were collected at predetermined time intervals of 20, 40, and 60 minutes to monitor the degradation process(28). These collected samples were further filtered to remove any residual particles present. Finally, the absorbance of the treated samples was measured using UV–Visible spectrophotometer to evaluate the extent of pharmaceutical degradation.

Fig 4.1 Experimental setup of UV photocatalytic reactor

4.3. Degradation Efficiency Calculation

The degradation efficiency of the methylene blue dye compound is calculated using the following



equation:

$$\text{Degradation Efficiency (\%)} = \frac{C_0 - C}{C_0} \times 100$$

Where:

C_0 =Initial concentration of the pollutant

C = Concentration after treatment

5. RESULT AND DISCUSSION

This chapter presents the experimental results obtained from the photocatalytic degradation of amoxicillin using the **iron nano particle –UV reactor system**. The performance of the system was evaluated based on the reduction in absorbance values measured using a UV–Visible spectrophotometer at 254 nm(30). The degradation efficiency was calculated at different time intervals to analyze the effectiveness of the treatment process.

TABLE 1: ABSORBANCE AND DEGRADATION EFFICIENCY

Time (min)	Absorbance	Degradation Efficiency (%)
0	1.000	0
20	0.900	10
40	0.500	50
60	0.100	76

5.1. Experimental Observations

The degradation of methylene blue dye was monitored at different reaction times (20, 40, and 60 minutes). The absorbance values decreased with increasing irradiation time, indicating the breakdown of methylene blue dye.

5.2. Effect Of Reaction Time

The degradation efficiency increased significantly with reaction time:

- At **20 minutes**, only partial degradation occurred
- At **40 minutes**, degradation reached a moderate level
- At **60 minutes**, maximum degradation (~76%) was achieved

This indicates that longer UV exposure enhances the breakdown of amoxicillin molecules due to increased interaction with hydroxyl radicals.

5.3. Effect of UV Irradiation

UV light at 254 nm played a crucial role in the degradation process by providing sufficient energy to initiate multiple reactions. The ultraviolet radiation helped break the chemical bonds present in methylene blue dye, leading to its structural degradation. At the same time, it activated the iron nanoparticles present in the system, enhancing their catalytic activity. This activation resulted in the generation of highly reactive hydroxyl radicals ($\bullet\text{OH}$), which are powerful oxidizing agents. These radicals rapidly reacted with and oxidized the

methylene blue dye compounds, thereby significantly improving the efficiency of the degradation process.

5.4. Role of Iron Nano Particle

The iron nano *Particle* significantly improved the overall treatment efficiency:

- Initial degradation of pollutants through adsorption
- Reduction in turbidity, allowing better UV penetration
- Enhanced catalytic activity leading to higher radical generation
- This confirms the synergistic effect of combining membrane filtration with UV treatment.

CONCLUSION

This study demonstrated the green synthesis, fabrication, characterization, and application of a iron nanoparticle for advanced wastewater treatment. Iron oxide nanoparticles were synthesized using *Punica granatum* peel extract as a sustainable reducing and stabilizing agent, eliminating the need for toxic chemicals. Characterization techniques such as DLS and FTIR confirmed the formation, stability, and organic capping of nanoparticles. Furthermore, the integrated iron nano particle–UV reactor system showed high efficiency in degrading pharmaceutical contaminants, achieving up to 76% degradation of methylene blue dye within 60 minutes. The synergistic combination of adsorption, membrane filtration, and UV-induced advanced oxidation significantly improved degradation performance. Overall, the study highlights a sustainable, efficient, and eco-friendly approach for the treatment of methylene blue dye wastewater, promoting the advancement of green nanotechnology in environmental engineering applications.

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