

Magnetically Recyclable MoS₂/TiO₂ Binary Photocatalyst for Visible-Light Degradation of Levofloxacin

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Abstract

A binary MoS₂/TiO₂ magnetic composite (MMT) was synthesized and evaluated as a photocatalyst for the degradation of levofloxacin (LFX), a pharmaceutical pollutant. The structure and properties of MMT were characterized by FT-IR, XRD, EDX, VSM, and SEM. The composite exhibits strong magnetic properties, enabling easy magnetic recovery and reuse. Optimization experiments showed that pH, contact time, and catalyst dosage significantly influence LFX degradation. The highest degradation efficiency occurred at pH 6, with a catalyst dose of 50 mg and a reaction time of 60 minutes. At an initial LFX concentration of 10 mg/L, the MMT composite achieved 96% degradation. Furthermore, the photocatalyst maintained more than 65% efficiency after five consecutive reuse cycles. These results indicate that the MoS₂/TiO₂ composite is an effective and magnetically recyclable photocatalyst for mitigating pharmaceutical pollutants in water.

Keywords: Magnetic Photocatalyst; Molybdenum Sulfide; Titanium Dioxide; Levofloxacin; Photodegradation.

Introduction

Rapid advancements in medicine, together with substantial industrial development, have significantly improved human living standards; however, these advancements have inadvertently exacerbated environmental pollution (1). Contaminants such as agricultural fertilizers, pesticides, organic compounds, heavy metals, and pharmaceutical effluents are major contributors to environmental degradation, posing health risks and threatening ecological stability (2). Among these, pharmaceutical residues have emerged as a

particularly critical concern. Classified as emerging contaminants, these residues originate from hospital effluents, human excreta, and pharmaceutical manufacturing discharges (3).

Antibiotics, in particular, are widely used for therapeutic and prophylactic purposes, and a significant fraction of their active compounds or metabolites is released into the environment annually (4). The persistent presence of antibiotics in soils and aquatic systems adversely affects ecosystem functionality and poses direct threats to human health. Specifically, antibiotics can inhibit photosynthetic activity in certain plant species

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and impede the natural biodegradation of organic matter (5). Levofloxacin (LFX), a broad-spectrum fluoroquinolone, exemplifies these concerns. Due to its chemical stability and high bioaccumulation potential, conventional degradation methods are often insufficient, highlighting the need for advanced remediation strategies (6).

Various approaches—including electrochemical oxidation, adsorption, biological treatment, and photocatalysis—have been explored for the removal of antibiotics. Among these, photocatalysis has emerged as a particularly promising technique, owing to its high efficiency, operational simplicity, and minimal risk of secondary pollution (7). Semiconductor-based photocatalysis, in particular, offers substantial potential for environmental applications, and numerous photocatalysts—including $g\text{-C}_3\text{N}_4$, TiO_2 , SnO_2 , BiVO_4 , ZnS , ZnO , and MoS_2 —have been extensively investigated for pollutant degradation (8).

Titanium dioxide (TiO_2) is widely recognized as an effective and robust photocatalyst due to its chemical and biological inertness, corrosion resistance, low cost, and high photosensitivity (9). Nevertheless, its inherent limitations, including a wide bandgap and rapid electron–hole recombination, limit its activity under visible light. Strategies such as metal or nonmetal doping and coupling with other semiconductors have been employed to enhance its photocatalytic performance in the visible-light region (10), leading to the development of multiphase TiO_2 -based photocatalyst systems with improved efficiency for environmental remediation.

Molybdenum disulfide (MoS_2) has recently attracted considerable attention for water treatment applications due to its tunable band structure, high surface area, and superior adsorption capacity. Its unique two-dimensional layered structure confers remarkable physicochemical and electronic properties (11). Despite its promising photocatalytic potential, the narrow band gap of MoS_2 limits both its stability and overall photocatalytic efficiency. Coupling MoS_2 with other semiconductors to form heterojunction structures has proven an effective strategy to overcome these limitations and enhance charge separation (12).

Environmental contamination by antibiotics, particularly LFX, represents a serious threat to both ecosystem integrity and human health. Given the challenges posed by LFX degradation and its adverse effects on soil and groundwater, advanced remediation technologies, such as photocatalysis, are essential. In this context, the present study focuses on the development of magnetic nanocomposites based on MoS_2 and TiO_2 to achieve efficient LFX degradation. These composites are designed to enhance photocatalytic efficiency while

minimizing secondary pollution, offering a practical solution for the management of pharmaceutical contaminants.

In the synthesized composite, MoS_2 extends the photocatalytic activity of TiO_2 into the visible-light region, while TiO_2 stabilizes the composite and enhances overall performance (13). Magnetic ZnFe_2O_4 ferrite was incorporated to produce a magnetic $\text{MoS}_2/\text{TiO}_2$ nanocomposite. Although ZnFe_2O_4 , with a narrow band gap of 1.90 eV, possesses potential for organic pollutant degradation, its intrinsic photocatalytic activity is relatively low. Coupling ZnFe_2O_4 with TiO_2 and MoS_2 generates a composite with improved photocatalytic and magnetic properties (14). This dual-heterostructure nanocomposite was applied for the photodegradation of LFX, with key operational parameters—including pH, contact time, and catalyst dosage—systematically optimized. The photocatalytic performances of MoS_2 , $\text{MoS}_2/\text{TiO}_2$, and $\text{MoS}_2/\text{ZnFe}_2\text{O}_4$ composites were evaluated and compared with the magnetic nanocomposite.

This study introduces several notable innovations in the field of photocatalysis and the degradation of pharmaceutical pollutants. First, a novel $\text{MoS}_2/\text{TiO}_2$ -based nanocomposite was synthesized, functioning as a recyclable magnetic photocatalyst. The study systematically investigates the synergistic effects of combining MoS_2 and TiO_2 within a magnetic framework, whereas previous research largely focused on their individual photocatalytic properties.

Second, the demonstrated recyclability of the magnetic $\text{MoS}_2/\text{TiO}_2$ (MMT) photocatalyst over multiple operational cycles enhances both economic feasibility and sustainability, which is advantageous for potential industrial applications.

Third, the optimization of photocatalytic process parameters resulted in up to 96% degradation of levofloxacin (LFX). Comparative evaluations of $\text{MoS}_2/\text{TiO}_2$ and $\text{MoS}_2/\text{ZnFe}_2\text{O}_4$ further highlighted the superior photocatalytic performance of the MMT composite in pollutant removal.

Collectively, these findings underscore the scientific significance and practical relevance of this work, demonstrating a promising approach for the effective management of pharmaceutical contaminants in environmental remediation applications.

Materials and Methods

Materials and Instrumentation

All reagents used in this study were of analytical grade and obtained from Merck and Sigma-Aldrich. The synthesized magnetic photocatalyst was thoroughly

characterized using a combination of advanced techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), photoluminescence spectroscopy (PL), diffuse reflectance spectroscopy (DRS), scanning electron microscopy (SEM), and vibrating sample magnetometry (VSM).

XRD patterns were recorded using a Philips X'Pert MPD diffractometer with Cu-K α radiation ($\lambda = 1.540589$ Å). FT-IR spectra were collected over the wavenumber range of 4000–400 cm⁻¹. The concentration of levofloxacin (LFX) was quantified using a PerkinElmer Lambda 45 UV–Vis spectrophotometer. Photocatalytic activity was evaluated under irradiation from a 10 W LED lamp. PL measurements were performed with a PerkinElmer LS55 spectrometer, while DRS spectra were acquired using a Scinco S-4100 instrument.

For magnetic separation of the photocatalyst from aqueous solutions, a neodymium–iron–boron (Nd–Fe–B) magnet with a magnetic field strength of 1.31 T was used, ensuring rapid and efficient catalyst recovery for subsequent reuse.

Synthesis of the MMT Photocatalyst

MoS₂ nanoparticles were synthesized according to previously reported procedures (15). Briefly, 70 mL of deionized water containing cetyltrimethylammonium bromide (CTAB) was stirred for 20 min to obtain a homogeneous solution. Subsequently, ammonium heptamolybdate tetrahydrate ((NH₄)₆Mo₇O₂₄·4H₂O) and thiourea (C₂H₅NS) were added and stirred for an additional 10 min until complete dissolution. The mixture was transferred to a 100 mL Teflon-lined stainless-steel autoclave and heated at 180 °C for 18 h. After cooling to room temperature, the reaction mixture was centrifuged to yield the solid product. The solid was washed three times with deionized water and ethanol. Finally, it was dried at 60 °C for 6 h.

To synthesize the MoS₂/TiO₂ binary photocatalyst, 1 mL of titanium (IV) butoxide (Ti (OBu)₄) was dissolved in 25 mL of ethylene glycol at room temperature. This solution was added dropwise under vigorous stirring to 50 mL of an aqueous suspension containing a predetermined amount of MoS₂. The suspension was transferred to a 100 mL Teflon-lined autoclave and reacted at 200 °C for 12 h. The resulting light gray precipitate was collected by centrifugation. It was washed with ethanol and water. The product was dried at 60 °C for 6 h. For the magnetic photocatalyst, 0.5 g of MoS₂ or MoS₂/TiO₂ was ultrasonically dispersed in 10 mL of ethylene glycol for 1 h. Then, 0.6 g of zinc nitrate and 1.7 g of hydrated iron nitrate (Fe(NO₃)₃·6H₂O) were dissolved in 20 mL of deionized water, and the

suspension was sonicated for 5 min. Approximately 2 mL of 5 M NaOH was added dropwise, and the mixture was further sonicated at 60 °C for 1 h. The resulting magnetic MoS₂/TiO₂ (MMT) photocatalyst was collected by applying an external magnetic field. It was washed with deionized water and dried at 60 °C for 24 h.

Photocatalytic Degradation of LFX

Photocatalytic degradation experiments were conducted in a photochemical reactor equipped with a 10 W LED lamp and a magnetic stirrer. A predetermined amount of the synthesized photocatalyst (50 mg) was added to 100 mL of aqueous LFX solution (10 mg L⁻¹) at pH 6 under dark conditions to establish adsorption–desorption equilibrium. The reaction was then initiated under LED irradiation.

After the reaction, the photocatalyst was separated from the solution using either an external magnetic field or centrifugation. The residual LFX concentration was determined via UV–Vis spectrophotometry at 288 nm. The removal efficiency (R %) was calculated as:

$$R\% = [(C_0 - C_e)/C_0] \times 100$$

where C_0 is the initial LFX concentration, and C_e is the equilibrium concentration after photocatalysis.

Results and Discussion

Characterization of the Photocatalyst Structure

The FT-IR spectra of MoS₂, MoS₂/TiO₂, MoS₂/ZnFe₂O₄, and the magnetic MoS₂/TiO₂ (MMT) composite are shown in Figure 1. In the MoS₂ composite, the absorption band at ~1622 cm⁻¹ corresponds to O–H bending vibrations. A peak around 1700 cm⁻¹ is attributed to Mo–S stretching, and the band near 1150 cm⁻¹ is associated with sulfate groups (16).

The MoS₂/TiO₂ composite exhibits characteristic peaks at 3250 and 1620 cm⁻¹, corresponding to O–H stretching and bending vibrations, indicating the presence of surface hydroxyl groups from adsorbed water (17). A prominent peak at 600 cm⁻¹ corresponds to the Ti–O stretching mode, characteristic of TiO₂.

In the MoS₂/ZnFe₂O₄ composite, absorption bands in the range 450–650 cm⁻¹ are assigned to Fe–O and Zn–O stretching vibrations within the octahedral and tetrahedral sites of ZnFe₂O₄ nanoparticles. Additional bands around 1600 and 3300 cm⁻¹ are attributed to the bending and stretching vibrations of adsorbed water molecules (18).

The FT-IR spectrum of the MMT composite displays characteristic peaks of all individual components, including metal oxide vibrations, Mo–S stretching, and H₂O stretching modes, confirming the successful synthesis of the ternary composite.

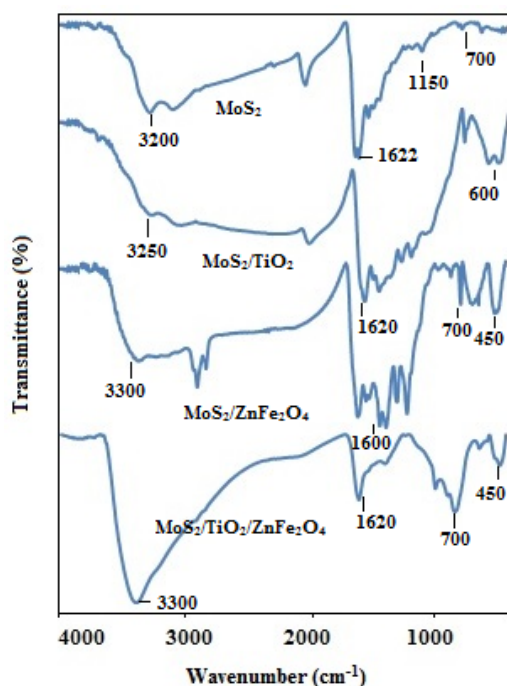


Figure 1. FT-IR spectra of the synthesized composites

The elemental composition of the MMT nanocomposite was further analyzed using energy-dispersive X-ray spectroscopy (EDX). As shown in Figure 2, all elements corresponding to the nanocomposite components were clearly detected in the EDX spectrum. Sulfur and molybdenum, originating from MoS_2 , constitute the main components of the nanocomposite, with relative abundances of 5.5% and 28.7%, respectively. Other elements present in the nanohybrid, including Ti, O, Zn, and Fe, were also observed, confirming the successful synthesis of a high-density ternary composite.

The XRD patterns of MoS_2 , $\text{MoS}_2/\text{TiO}_2$, $\text{MoS}_2/\text{ZnFe}_2\text{O}_4$, and MMT composites are presented in Figure 3. The observed peaks can be assigned to the (002), (004), (100), (102), and (110) diffraction planes, respectively. The broadening of the peaks is attributed to small crystallite sizes (19).

The XRD pattern of the MMT composite exhibits sharp and intense peaks corresponding to TiO_2 at 2θ values of 28.2° , 37.8° , 48.1° , 52.5° , and 62.3° , which are assigned to the (101), (004), (200), (105), and (213) crystal planes, respectively (19).

The XRD pattern of the ferrite-containing nanohybrid shows characteristic peaks of Zn–ferrite nanoparticles at 2θ values of 30.1° , 35.4° , 44.2° , 66.7° , and 68.1° ,

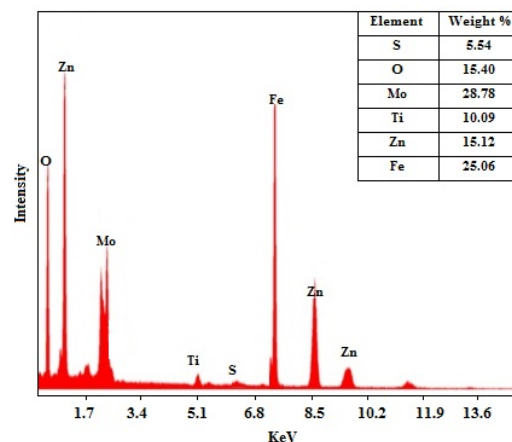


Figure 2. EDS analysis of the MMT ternary composite

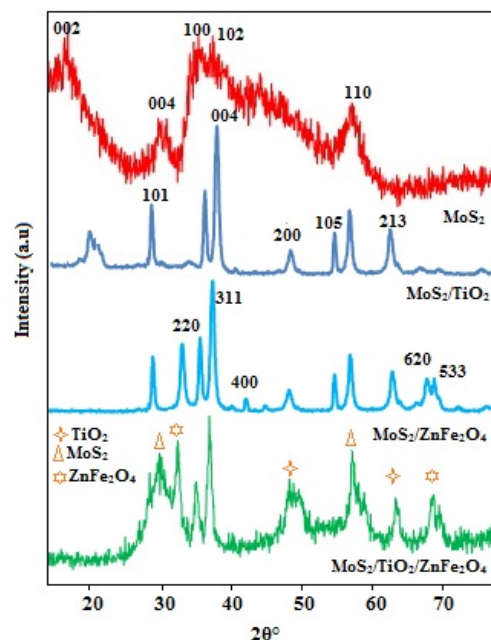


Figure 3. XRD patterns of the synthesized composites

corresponding to the (220), (311), (400), (620), and (533) planes, respectively (20).

These results confirm that the MoS_2 surface is effectively and uniformly coated with TiO_2 and ferrite nanoparticles.

The morphology of the synthesized materials was examined using scanning electron microscopy (SEM), and the results are presented in Figure 4. As shown in Figure 4a, MoS_2 exhibits a bare, sheet-like structure composed of stacked nanoparticles with irregular, amorphous surfaces (21). The MMT composite displays a porous morphology, as TiO_2 appears as fibrous

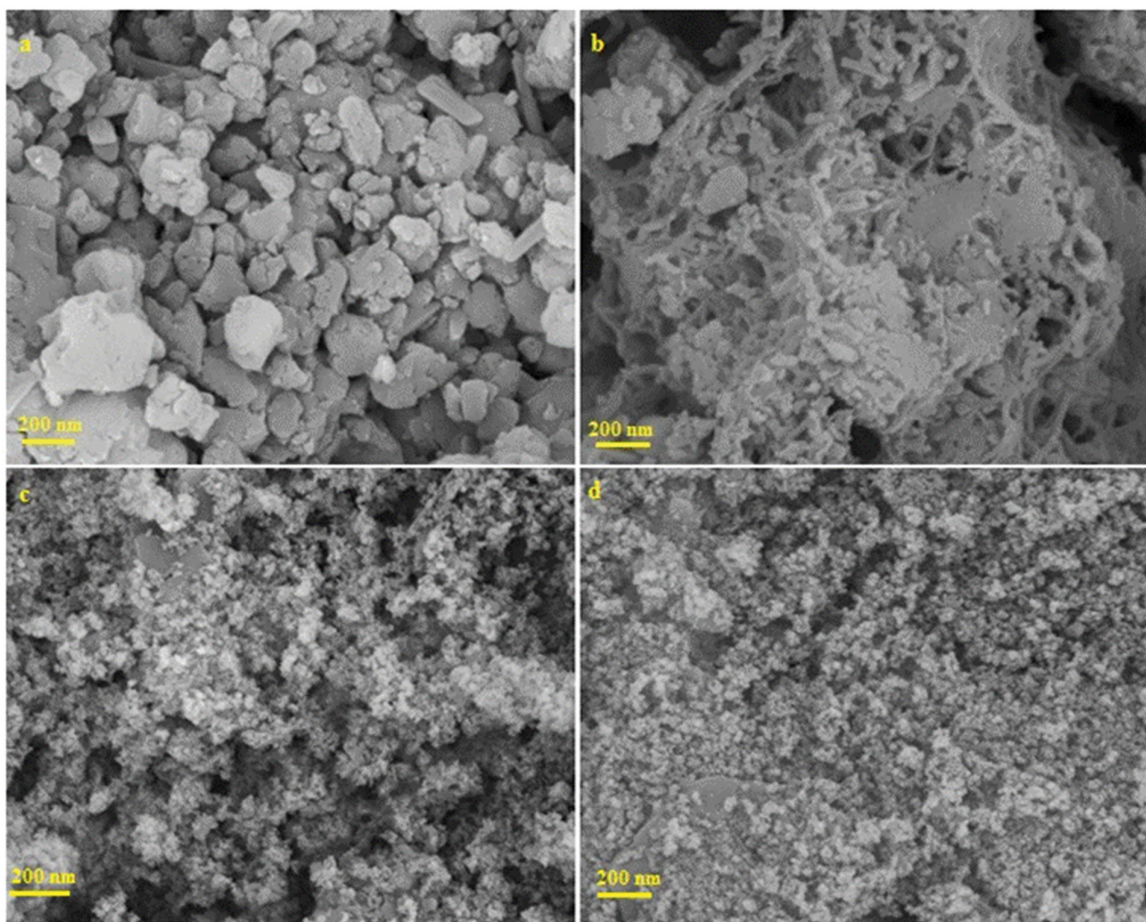


Figure 4. SEM images of the synthesized composites: MoS₂ (a), MoS₂/TiO₂ (b), MoS₂/ZnFe₂O₄ (c), and MMT (d)

structures on the surface of MoS₂ (Figure 4b).

SEM images of MoS₂/ZnFe₂O₄ and the magnetic MMT composite are shown in Figures 4c and 4d, respectively, revealing that the synthesized particles exhibit irregular, nanoscale spherical structures. The ferrite nanoparticles are uniformly distributed on the MoS₂ and MoS₂/TiO₂ substrates, forming spherical structures with diameters below 200 nm. The small particle size increases the active surface area, thereby enhancing photocatalytic performance.

These observations confirm that both ferrite and TiO₂ nanoparticles are well-dispersed on the MoS₂ surface, indicating the successful fabrication of the ternary composite.

The magnetic properties of the synthesized ZnFe₂O₄ ferrite, the MoS₂/ZnFe₂O₄ composite, and the MMT composite were investigated using vibrating sample magnetometry (VSM). The as-synthesized ZnFe₂O₄

nanoparticles exhibited a saturation magnetization of 28 emu g⁻¹ (Figure 5). The MoS₂/ZnFe₂O₄ and MMT composites displayed lower saturation magnetizations of 15 emu g⁻¹ and 7.5 emu g⁻¹, respectively (22). This reduction in magnetization is attributed to the presence of non-magnetic MoS₂ and TiO₂ layers within the composite structure.

The magnetic nature of the composites enables their facile separation from aqueous solutions using an external magnetic field during antibiotic degradation, preventing secondary environmental contamination. Furthermore, this property enables easy recovery and reuse of the photocatalyst.

Effect of pH on Photocatalytic Degradation

To investigate the effect of solution pH on the photocatalytic degradation of LFX, experiments were conducted at pH 3-9 for 60 min. The pH was adjusted

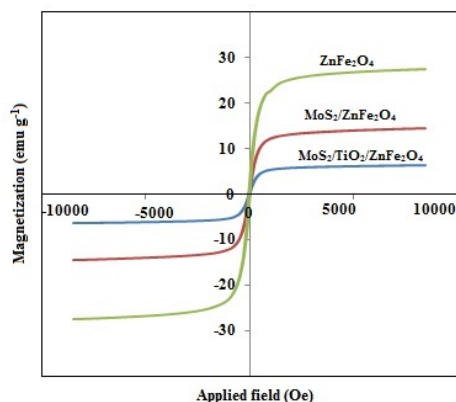


Figure 5. VSM curves of ZnFe_2O_4 ferrite and the synthesized composites

using 0.1 M HCl and 0.1 M NaOH. The initial LFX concentration was 10 mg L^{-1} , and the photocatalyst dosage was 50 mg.

As shown in Figure 6, the solution pH strongly affects the degradation efficiency. The highest photocatalytic performance was observed at approximately pH 6, whereas increasing pH further resulted in a noticeable decrease in the degradation rate. This trend can be explained by considering the photocatalyst's surface charge and the speciation of LFX at different pH values (23).

The magnetic MMT composite is neutral or slightly negatively charged at pH values near 6–7. In addition, LFX exhibits a positive charge near neutral pH (Figure 7a), facilitating its adsorption onto the photocatalyst

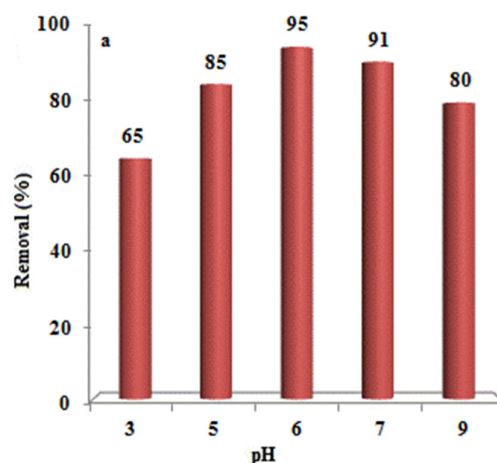


Figure 6. Effect of pH on the photocatalytic degradation of LFX

surface through electrostatic attraction. The UV–Vis spectra of the composites during LFX degradation at different time points indicate LFX degradation (Figure 7b). After 60 minutes, the lowest intensity of λ_{max} was observed. This indicates that LFX is degraded over time under UV irradiation in the presence of the photocatalyst, to the point that λ_{max} is diminished at 60 minutes. This means that the sample degrades completely at 60 minutes, and longer UV irradiation times are practically ineffective.

Under alkaline conditions, the carboxylic acid group of LFX becomes deprotonated, carrying a negative charge. This results in electrostatic repulsion from the negatively charged photocatalyst surface, thereby reducing degradation efficiency. Other interactions that

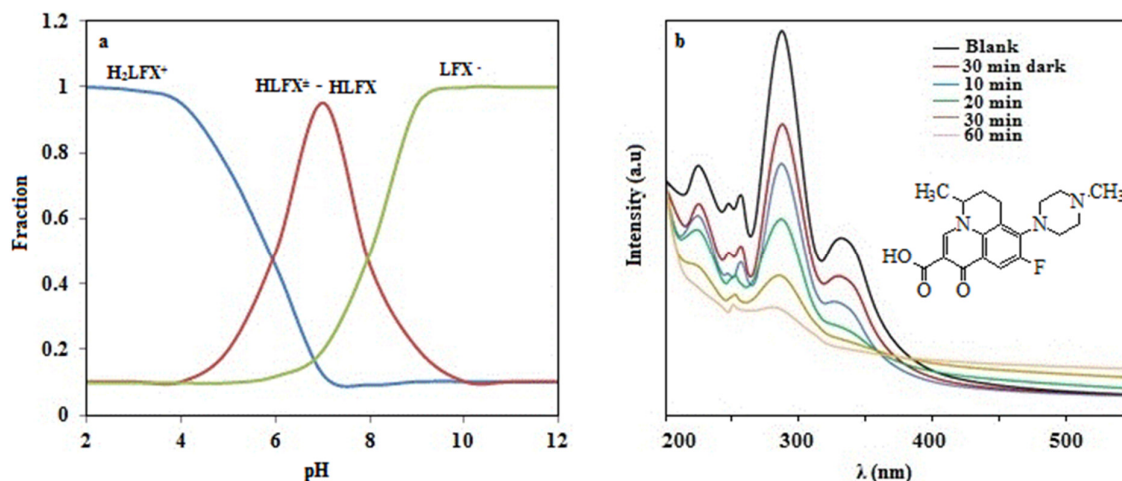


Figure 7. (a) Speciation of LFX as a function of pH and (b) UV–Vis spectra of the composites during LFX degradation at different time intervals

promote LFX adsorption include hydrogen bonding between the oxo/hydroxy groups on the photocatalyst surface and the amino/carboxyl groups of LFX, which further enhance photocatalytic activity (24).

Effect of Reaction Time and Catalyst Dosage

The influence of **reaction time** on the photocatalytic degradation of LFX was evaluated using an initial concentration of 10 mg L⁻¹ in 100 mL of solution at pH 6, over 10–60 min, with a catalyst dosage of 50 mg. The degradation kinetics are presented in Figures 8a and 8b. The results indicate that LFX undergoes negligible photodegradation in the absence of the photocatalyst. Furthermore, after 30 min in the dark, approximately 25% of LFX was removed via adsorption onto the catalyst surface.

The degradation efficiency increased with longer reaction times, reaching a maximum after 60 min. The effect of catalyst dosage was also investigated using MMT at 25, 50, 100, and 150 mg. As shown in Figure 8b, the degradation efficiency increased significantly when the dosage was raised from 25 to 50 mg, likely due to a higher density of active species and more available catalytic sites for interaction with LFX molecules. However, further increases in catalyst dosage led to a decrease in degradation efficiency, likely due to overlapping active sites at high concentrations, which

hinder analyte access to the catalyst surface.

Based on these observations, the maximum photocatalytic degradation efficiency of LFX (10 mg L⁻¹) was 96% under the optimized conditions: pH 6, reaction time 60 min, and a catalyst dosage of 50 mg MMT.

The photocatalytic activity of the magnetic photocatalyst was compared with MoS₂, MoS₂/TiO₂, and MoS₂/ZnFe₂O₄ under optimized conditions at an LFX concentration of 10 mg L⁻¹. As summarized in Table 1, the degradation efficiency of pristine MoS₂ nanoparticles was 75%, which increased to 80% and 83% upon combination with TiO₂ and ZnFe₂O₄, respectively. Under identical conditions, the magnetic MMT composite achieved a markedly higher degradation efficiency of 96%.

The relatively lower performance of MoS₂ alone can be attributed to the rapid recombination of photogenerated electrons and holes, which limits its photocatalytic activity (25). Incorporation of TiO₂ and ferrite nanoparticles effectively suppresses charge recombination, thereby enhancing the composite's overall photocatalytic efficiency.

It can be concluded that the above results are in good agreement with the bandgap energies of the materials (Table 2).

The band gap of a nanoparticle is a key factor influencing its photocatalytic performance. Defined as

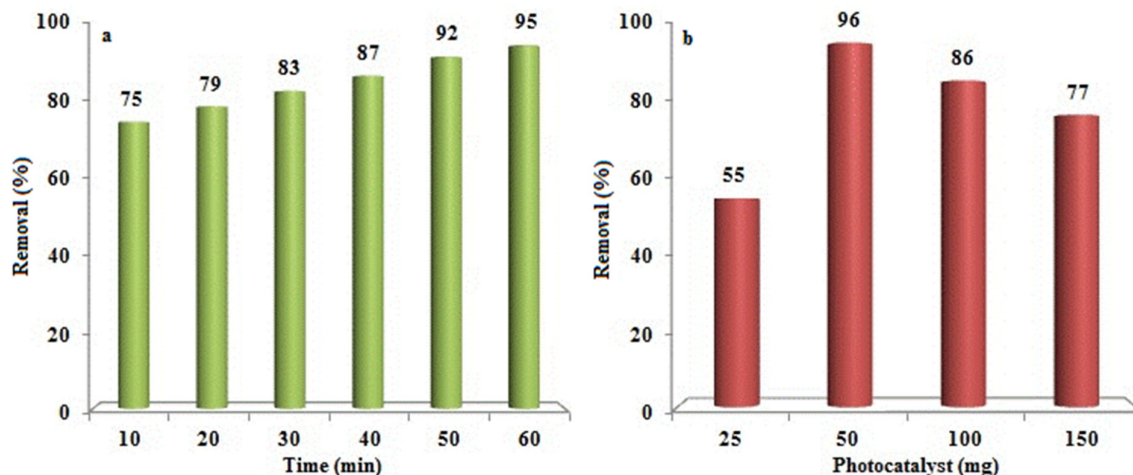


Figure 8. Effect of contact time and magnetic MMT photocatalyst dosage on the photocatalytic degradation of LFX

Table 1. Photocatalytic degradation efficiency of LFX using different photocatalysts

Degradation (%)	K(min ⁻¹)	R ²	Photocatalyst
75	0.006	0.92	MoS ₂
80	0.008	0.99	MoS ₂ /TiO ₂
83	0.004	0.86	MoS ₂ /ZnFe ₂ O ₄
96	0.032	0.95	MMT

Table 2. Bandgap energies of the synthesized composites

Band gap Eg [eV]	Photocatalyst
1.67	MoS ₂
1.90	TiO ₂ (Bulk)
0.52	MoS ₂ /TiO ₂
0.45	MoS ₂ /TiO ₂ /ZnFe ₂ O ₄ (NMT)

the energy difference between the valence band and the conduction band, the band gap determines the material's ability to absorb light and generate excited electrons. For an efficient photocatalyst, the band gap must be appropriately tuned to enable absorption of visible or ultraviolet light.

Materials with a band gap smaller than 3 eV typically absorb visible light and are thus more suitable for photocatalytic applications under natural illumination. A reduction in the band gap of composites indicates an enhanced capacity for visible-light absorption, which is highly beneficial for photocatalytic processes. Band gap engineering through nanoparticle design and composite formation can therefore optimize both light absorption and photocatalytic performance.

As shown in Table 2, composites such as MoS₂/TiO₂, MoS₂/ZnFe₂O₄, and MMT exhibit higher photocatalytic activity compared to their individual components. This improvement is attributed to enhanced surface interactions and more efficient charge transfer between the components (26).

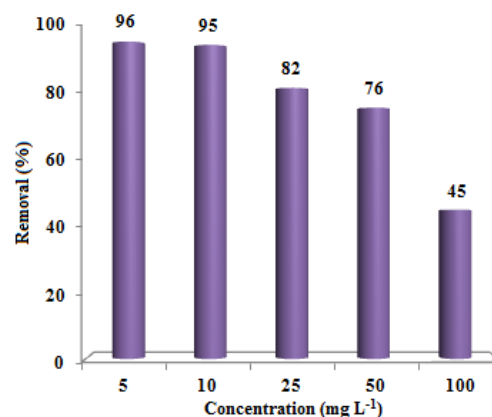
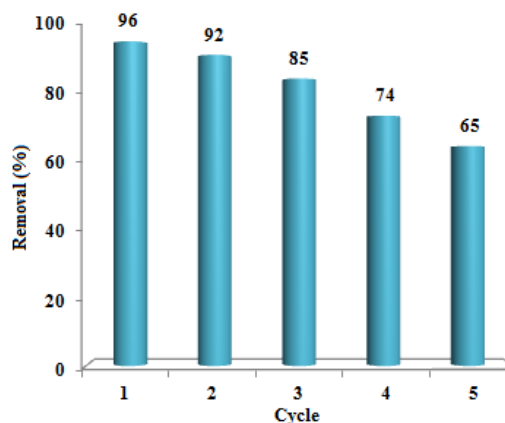
Photocatalytic Performance at Different LFX Concentrations

The magnetic MMT composite was used to evaluate the effect of LFX concentration on the photocatalytic degradation rate under optimized conditions: 50 mg catalyst dosage, pH 6, and 60 min reaction time. The LFX concentration was varied from 5 to 100 mg L⁻¹.

As shown in Figure 9, increasing the LFX concentration decreased the degradation efficiency from 96% to 45%. This decline can be attributed to reduced light penetration in solutions with higher LFX concentrations, which limits the amount of light reaching the photocatalyst surface and consequently reduces photocatalytic activity (27).

Reusability

The recyclability of the photocatalyst was evaluated by collecting it from the solution, washing it with a NaOH/ethanol mixture, and rinsing with distilled water. The MMT composite was then dried at 60 °C for 4 h and subsequently reused for LFX photodegradation under the same experimental conditions described above.

**Figure 9.** Effect of LFX concentration on photocatalytic degradation efficiency**Figure 10.** Number of photocatalytic degradation cycles of LFX using the magnetic MMT composite

As illustrated in Figure 10, the photocatalyst maintained an LFX removal efficiency of 65% after five consecutive cycles, demonstrating that the MMT composite is a reusable magnetic photocatalyst with satisfactory performance and stability.

During repeated photocatalytic cycles, the active sites of the photocatalyst may become blocked by adsorbed pollutants and their degradation products, leading to a decrease in catalytic efficiency (28). Additionally, under operational conditions, the photocatalyst may undergo structural changes, leading to reduced photocatalytic activity. The accumulation of by-products or organic residues on the catalyst surface can further degrade performance and contribute to efficiency losses (29).

To enhance photocatalyst stability, reaction conditions can be optimized. Adjusting parameters such as pH, temperature, and contact time can help minimize by-product accumulation and improve overall performance. After multiple cycles, catalyst regeneration

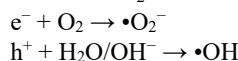
methods—including chemical washing and vacuum oven treatment—can be used to clean the surface and restore activity. Moreover, the use of nanocomposites or a combination with other materials can improve stability and reduce efficiency loss during repeated cycles.

Mechanistic Discussion

As shown in Figure 11, under visible-light irradiation, MoS₂ and ZnFe₂O₄ components absorb photons and generate electron–hole pairs. The subsequent transfer and separation of these charge carriers at the MoS₂/TiO₂ and MoS₂/ZnFe₂O₄ interfaces create a sustained population of reactive species that drive the oxidative degradation of LFX. The enhanced activity of the ternary MMT composite relative to the binary components is attributed to improved charge separation, extended light absorption, and increased interfacial contact, which reduce electron–hole recombination.

MoS₂ has a narrower bandgap, enabling visible-light excitation. TiO₂ provides a robust, wide-bandgap partner, while ZnFe₂O₄ introduces ferrite states that broaden the absorption spectrum and offer additional pathways for charge migration. In the MoS₂/TiO₂ junction, a favorable band alignment facilitates efficient separation of photogenerated electrons and holes: electrons migrate

toward the TiO₂-rich region, while holes accumulate on the MoS₂ surface. This spatial separation suppresses recombination and prolongs charge-carrier lifetimes, enabling sustained ROS generation. In the MMT ternary system, ferrite and TiO₂ layers act as barriers/bridges that enable more effective electron transport, further suppressing recombination, and promoting formation of ROS such as •O₂[−] and •OH via:



The observed reduction in bandgap energy for the composites (reported in Table 2) supports enhanced visible-light harvesting, resulting in higher steady-state ROS production under the same irradiation conditions.

Conclusion

The magnetic MMT-based MoS₂/TiO₂/ZnFe₂O₄ photocatalyst demonstrates efficient, recyclable degradation of LFX under visible-light irradiation. Under optimized conditions (pH 6, 60 min, 50 mg), 96% LFX removal was achieved, which, when compared with recent MoS₂/TiO₂ and ternary-catalyst reports, is competitive or superior in similar time frames and at comparable or lower loadings. The MoS₂ contribution enhances performance relative to the commonly reported

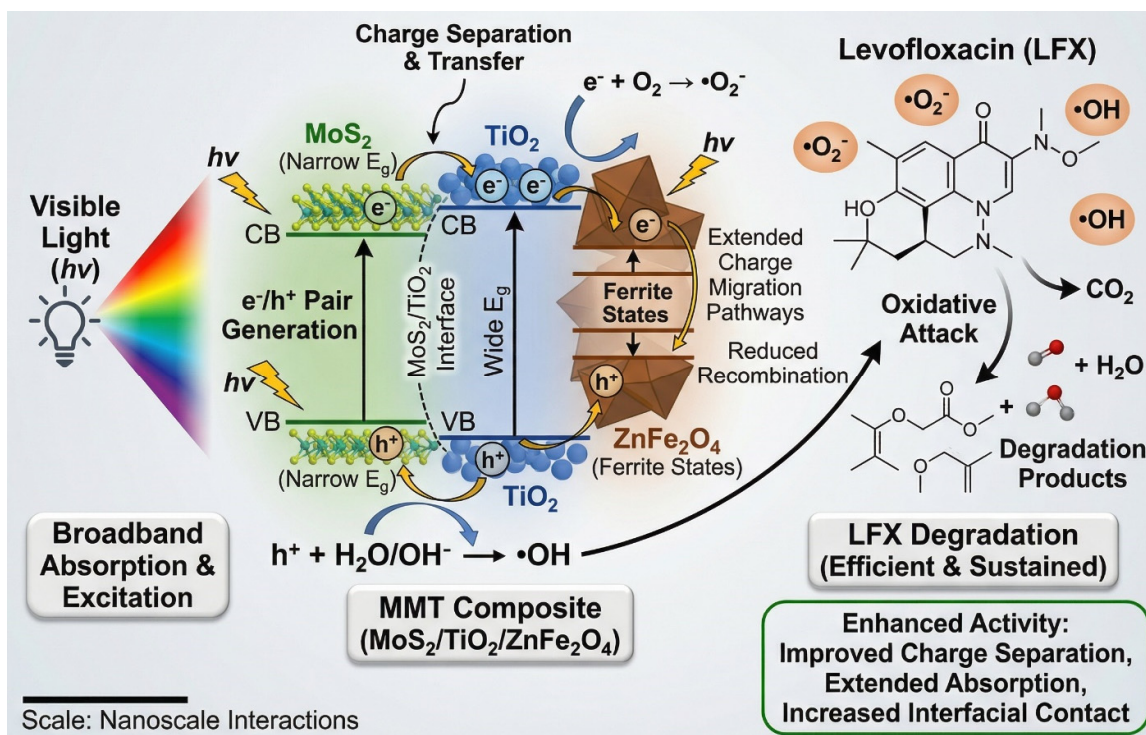


Figure 11. Enhanced visible light photocatalytic LFX degradation over MoS₂/TiO₂/ZnFe₂O₄ composite

binary MoS₂ systems. The catalyst shows good reusability, retaining 65% of its activity after five cycles, which is favorable compared with several reports in which activity decays more rapidly. Magnetic separability further reduces the risk of secondary contamination. Overall, our results advance recyclable, visible-light photocatalysts for emerging contaminants and provide a framework for benchmarking against current literature.

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