

Magnetically Recoverable BiVO₄/Fe₃O₄/g-C₃N₄ Photocatalyst via One-Pot Hydrothermal Synthesis for Visible-Light Methylene Blue Degradation

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Abstract

The development of efficient and recyclable photocatalysts offers promising alternatives for wastewater treatment. However, significant challenges remain, including inefficient light utilization for photodegradation and rapid charge-carrier recombination. This study aims to synthesize a distinctive reusable BiVO₄/Fe₃O₄/g-C₃N₄ (BNFC) photocatalyst with magnetic recovery via a one-pot hydrothermal method for visible-light methylene blue (MB) degradation. The optimal composite, BNFC-0.5, exhibited superior photocatalytic performance, achieving a degradation efficiency of 93.04% under optimal conditions of catalyst composition, pH 9, and 160 minutes of irradiation, with a TOC mineralization efficiency of 42.48%. The high degradation efficiency of the BNFC-0.5 composite is ascribed to its enhanced ability to harvest visible light, facilitate electron excitation with lower energy input, and promote effective electron-hole migration via the proposed Z-scheme configuration. Evaluation of the reactive oxygen species revealed that hydroxyl radicals (OH) made the greatest contribution to the oxidation of MB. Kinetic assessment of the photocatalytic process revealed that the experimental behavior was adequately described by the Langmuir-Hinshelwood model, indicating a pseudo-first-order degradation pathway. In addition, the photocatalyst maintained a degradation efficiency of 79.32% over four cycles, demonstrating good stability and reusability, which is supported by the composite's good structural stability. Overall, the findings demonstrate that constructing a ternary heterojunction is an effective strategy for enhancing the composite's photocatalytic capability. Owing to its high degradation efficiency and reusability, the composite represents a promising candidate for wastewater purification under visible-light conditions.

Keywords

Photocatalysis, Methylene Blue Degradation, Ternary Heterojunction, Magnetic Photocatalyst, Visible-Light Irradiation

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1. INTRODUCTION

Water pollution is a significant concern due to the crucial role of water in everyday life. Approximately 200,000 tons of dye-containing textile wastewater contaminate water bodies annually. The continuous discharge of contaminated wastewater into receiving waters can degrade environmental quality and pose potential hazards to human health. Industrial wastewater containing dyes reduces the penetration of sunlight into the air, thus impacting aquatic biota (Saini and Dey, 2022). Low air solubility and low fixation rates make it easy for dyes from the textile industry to be carried into the air and become pollutants. Approximately 10–15% of total synthetic dye production is carried into water bodies (Singh et al., 2024). Among synthetic colorants used in industrial manufacturing, methylene blue (MB) is commonly selected for its heterocyclic aromatic molecular structure (Tooba et al., 2026). The discharge of untreated MB into water bodies can cause serious environmen-

tal problems, including contamination of aquatic ecosystems, disruption of aquatic food chains, and potential toxic effects on humans and animals (Hakim et al., 2024). MB has been reported to cause health problems in exposed individuals, such as nausea, dizziness, and heartburn (Purnomo et al., 2026). In addition, the presence of MB in aquatic environments can damage fish gill function and disrupt nutrient cycling due to the toxic effects of MB dyes on microbial communities (Abdelrahman et al., 2026). Therefore, the presence of MB in wastewater poses an environmental risk and requires effective treatment strategies to degrade it and reduce its ecological impact.

Various methods have been applied to address MB wastewater pollution, including coagulation, electrodialysis, nanofiltration, adsorption, and ozonation (Tayeh et al., 2026). However, these methods still require additional treatment steps for complete degradation and often require relatively long processing times (Bibi et al., 2023). One alternative method, consid-

ered more effective, efficient, sustainable, and environmentally friendly, is photodegradation. This process involves accelerating reactions that occur when a material, usually a semiconductor, interacts with light, generating Reactive Oxygen Species (ROS) that degrade pollutants (Celik et al., 2026). Compared with other available wastewater treatment such as adsorption, flocculation, and nanofiltration, photodegradation offers the advantage of decomposing MB into simpler and less harmful molecules rather than merely transferring pollutants from one phase to another, thereby minimizing secondary waste generation (Anju et al., 2026). Additionally, using renewable energy sources, such as ultraviolet and visible light, makes this method environmentally friendly, cost-effective, and sustainable (JP et al., 2026).

Bismuth-based semiconductors, particularly BiVO_4 , have attracted significant attention owing to their narrow band gap of approximately 2.3–2.4 eV, enabling visible-light activity and strong photocatalytic performance (Kamble et al., 2023). The crystal structure of BiVO_4 may appear as tetragonal scheelite, monoclinic scheelite, or tetragonal zircon, depending on the synthesis conditions. Among these structural forms, the monoclinic scheelite phase generally exhibits the highest photodegradation activity under visible-light beam (Vasiljević et al., 2026). Despite its potential, BiVO_4 as a photocatalyst exhibits significant limitations, including a high value of electron–hole (e^- – h^+) pair recombination and a relatively low adsorption capacity for pollutants (Qamar et al., 2024). The synthesis of $\text{BiVO}_4/\text{g-C}_3\text{N}_4$ composites is one solution to overcome these limitations (Panda et al., 2026). The photoactivity of graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) are attributed to its ability to absorb visible light, as evidenced by an approximative band gap of 2.7 eV and its stable physicochemical characteristics (Molaei, 2023). The combination of these two materials is promising because $\text{g-C}_3\text{N}_4$ serves as a supporting template, facilitating the building of an effective heterojunction with BiVO_4 and thereby optimizing charge separation and photocatalytic activity (Liang et al., 2026).

Recent reports have shown that incorporating oxides into $\text{g-C}_3\text{N}_4$ can increase ROS levels and improve charge-carrier performance. For example, the $\text{BiVO}_4/\text{g-C}_3\text{N}_4$ nanocomposite degrades MB, reaching 94% degradation after 90 minutes of irradiation (Nagarajan et al., 2026). Similarly, the $\text{ZnO}/\text{g-C}_3\text{N}_4$ composite degrades MB over 5 cycles, achieving a fixed degradation percentage of 90.12% (Chen et al., 2026). Other research reported that the degradation rate of $\text{TiO}_2/\text{g-C}_3\text{N}_4$ reached 95% after 100 minutes of irradiation. Incorporating $\text{g-C}_3\text{N}_4$ into the composite framework provides an appropriate matrix for interactions among the semiconductor phases, thereby improving degradation efficiency under photocatalytic conditions (Wahyuni et al., 2026). However, the use of such composites still faces challenges in practical applications, particularly in the separation and reuse of photocatalysts after the reaction, which are complicated and costly (Xu et al., 2020). One approach to address this challenge is the use of magnetic catalysts, which allow easy separation from the solution using

an external magnetic field without reducing their photocatalytic activity (Hanada et al., 2026). One magnetic material that has a strong magnetic response is magnetite (Fe_3O_4) (Hu et al., 2021). Fe_3O_4 is a ferrous ferrite compound widely used as a heterogeneous catalyst because it has strong magnetic properties, good stability, relatively low production costs, and is environmentally friendly (Ahmad et al., 2023).

A study by Avilés-Monreal et al. (2026) reported that the $\text{g-C}_3\text{N}_4/\text{Fe}_3\text{O}_4$ composite degraded MB by up to 90% within 120 minutes. In addition, the catalyst demonstrated excellent durability, maintaining a degradation efficiency of 85% after three reuse cycles, thanks to its magnetic properties, which facilitate separation. On the other hand, Bilal et al. (2025) report that ternary composites offer several advantages over single- or binary-component systems, as they can enhance charge separation through the interfaces among the three materials. In addition, the ternary heterojunction system provides multiple charge-migration pathways, facilitating efficient charge transport and thereby accelerating the oxidation-reduction reaction. This synergistic effect further improves degradation performance (Zulfa et al., 2024). For example, Zhao et al. (2020) reported that the $\text{BiVO}_4/\text{Fe}_3\text{O}_4/\text{rGO}$ nanocomposite achieved nearly 99% degradation efficiency within 120 min. The catalyst also exhibited excellent reusability, maintaining its photocatalytic performance for up to five consecutive cycles through facile recovery using an external magnetic field. Similarly, Taravati et al. (2025) reported that a $\text{g-C}_3\text{N}_4/\text{Fe}_3\text{O}_4/\text{CuO}$ composite achieved 90% MB degradation after 60 min of visible-light irradiation and maintained approximately 80% degradation efficiency after 6 reuse cycles. In addition, Delnavaz et al. (2025) reported that a $\text{g-C}_3\text{N}_4/\text{CeO}_2/\text{Fe}_3\text{O}_4$ composite achieved 97.5% MB degradation after 180 min of irradiation while maintaining excellent photocatalytic performance over five consecutive degradation cycles.

Despite these advances, the simultaneous integration of visible-light-responsive photocatalytic activity, magnetic recoverability, and compositional optimization within a one-pot-synthesized $\text{BiVO}_4/\text{Fe}_3\text{O}_4/\text{g-C}_3\text{N}_4$ (BNFC) heterojunction system remains underexplored. Therefore, this study developed a magnetically recoverable ternary BNFC heterojunction photocatalyst using a one-pot hydrothermal method. The one-pot hydrothermal approach offers several advantages, including simpler synthesis procedures, fewer processing steps, improved interfacial contact among composite components, and more homogeneous particle distribution, all of which are beneficial for heterojunction formation and interfacial charge-transfer interactions (Jabir et al., 2026).

The modification of $\text{g-C}_3\text{N}_4$ into the BiVO_4 -based system was intended to heighten visible-light absorption and may facilitate charge separation, thereby suppressing electron–hole recombination (Reddy et al., 2023). Meanwhile, Fe_3O_4 not only contributes to the heterojunction system but also enables efficient magnetic separation and catalyst recovery after photocatalytic degradation (Hou et al., 2025). Therefore, this work focuses on the synthesis, characterization, photocatalytic activ-

ity, and magnetic reusability of the BNFC ternary composite toward MB degradation.

2. EXPERIMENTAL SECTION

2.1 Materials

All chemicals employed in this work were of analytical grade, with no advance purification. Bismuth(III) nitrate pentahydrate ($\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$, Merck; MW = $485.07 \text{ g} \cdot \text{mol}^{-1}$), ammonium metavanadate (NH_4VO_3 , Aldrich, 99.0%; MW = $116.98 \text{ g} \cdot \text{mol}^{-1}$), sodium hydroxide (NaOH, Merck; MW = $40.00 \text{ g} \cdot \text{mol}^{-1}$), melamine ($\text{C}_3\text{H}_6\text{N}_6$, Loba Chemie, Germany; MW = $126.12 \text{ g} \cdot \text{mol}^{-1}$), Fe_3O_4 (Merck), MB (Merck; MW = $319.85 \text{ g} \cdot \text{mol}^{-1}$), absolute ethanol ($\text{C}_2\text{H}_5\text{OH}$, Merck; MW = $46.07 \text{ g} \cdot \text{mol}^{-1}$), hydrochloric acid (HCl, Merck; MW = $36.46 \text{ g} \cdot \text{mol}^{-1}$), nitric acid (HNO_3 , Aldrich, 65.0%; MW = $63.01 \text{ g} \cdot \text{mol}^{-1}$), sodium chloride (NaCl, Aldrich, 99.5%; MW = $58.44 \text{ g} \cdot \text{mol}^{-1}$), benzoquinone ($\text{C}_6\text{H}_4\text{O}_2$, Aldrich, 99.0%; MW = $108.09 \text{ g} \cdot \text{mol}^{-1}$), isopropyl alcohol ($\text{C}_3\text{H}_8\text{O}$, Merck; MW = $60.10 \text{ g} \cdot \text{mol}^{-1}$), ammonium oxalate ($(\text{NH}_4)_2\text{C}_2\text{O}_4$, Merck; MW = $124.10 \text{ g} \cdot \text{mol}^{-1}$), demineralized water, and distilled water.

Material characterization was conducted via X-ray diffraction (XRD) on a Shimadzu XRD-7000 with Cu $K\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) over $10\text{--}90^\circ$ to verify the crystal structure and phase composition of the obtained diffraction patterns. The surface morphology was examined using a Scanning Electron Microscope-Energy Dispersive X-ray Spectroscopy (SEM-EDX JEOL JSM-6520LA), which produced images with average particle size and morphology data. Furthermore, EDX analysis was used to determine the elemental composition and distribution of constituent elements in the material. In addition, UV-Vis diffuse reflectance spectroscopy (UV-Vis DRS) PerkinElmer Lambda 365 was employed to evaluate the material's capacity to absorb UV and visible light and to establish its band gap energy, Vibrating Sample Magnetometer (VSM) Oxford 1.2H was used to characterize magnetic materials and identify magnetic behavior; and Brunauer-Emmett-Teller (BET) Novatouch Lx4 was used to determine micropore volumes and micropore areas. Moreover, Total Organic Carbon (TOC) analysis was performed to evaluate the mineralization efficiency of MB during the photocatalytic degradation process by measuring the reduction of total organic carbon content after photocatalytic treatment using a Shimadzu TOC-L CPH.

2.2 Methods

2.2.1 Preparation of $\text{g-C}_3\text{N}_4$

Melamine (5 g) served as the precursor for $\text{g-C}_3\text{N}_4$ synthesis and was thermally treated at 550°C for 4 h with a heating rate of 5°C min^{-1} . After the furnace cooled naturally, the obtained material was mixed with 10 mL of ethanol and sonicated for 1 h to obtain exfoliated $\text{g-C}_3\text{N}_4$. This procedure was adapted from an earlier method established by our research group (Arieveali et al., 2025).

2.2.2 Preparation of $\text{BiVO}_4/\text{Fe}_3\text{O}_4/\text{g-C}_3\text{N}_4$ by one-pot - Hydrothermal Method

Initially, 4.85 g of $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ was dissolved in 40 mL of 2 M HNO_3 . In a separate container, 1.1698 g of NH_4VO_3 was dissolved in 20 mL of 2 M NaOH while being stirred at 600 rpm for 30 min. The vanadate solution was slowly poured to the bismuth precursor, and the mixture was stirred at 600 rpm for 1 h until a yellow suspension formed. The pH of the suspension was adjusted to 7 using 0.5 M NaOH and 0.5 M HCl. Subsequently, 0.0162 g of $\text{g-C}_3\text{N}_4$ and 0.646 g of Fe_3O_4 were incorporated into the suspension, followed by ultrasonication for 40 min in an ultrasonic bath to achieve a more homogeneous dispersion. The precursor concentrations and composition ratios of $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$, NH_4VO_3 , and Fe_3O_4 were adopted from previous studies on the synthesis of $\text{BiVO}_4/\text{Fe}_3\text{O}_4$ -based photocatalysts to maintain appropriate stoichiometry and heterojunction formation (Zhao et al., 2022). The prepared suspension was put in a 100 mL Teflon-lined autoclave for a hydrothermal treatment at 180°C for 16 h. The obtained solid was rinsed with distilled water and ethanol repeatedly to get rid of residual reactants, and further dried at 60°C for 24 h. BNFC composites containing 0%, 0.5%, 1%, and 2% $\text{g-C}_3\text{N}_4$, calculated relative to the BiVO_4 mass, were successfully prepared and designated as BNFC samples, as listed in Tabel 1. A schematic representation of the BNFC synthesis procedure is presented in Figure 1.

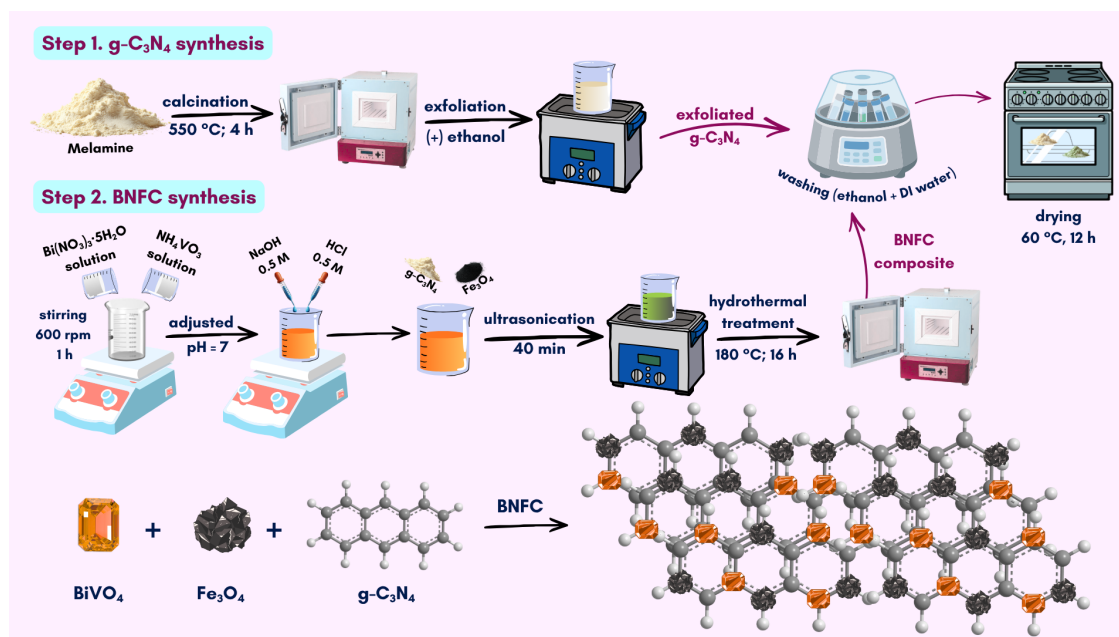
2.2.3 $\text{BiVO}_4/\text{Fe}_3\text{O}_4/\text{g-C}_3\text{N}_4$ Photocatalyst Optimum Condition

The photocatalytic performance of BNFC-0.5 toward MB degradation was optimized by evaluating the catalyst composition and the solution pH. Initially, 0.1 g of photocatalyst containing 0%, 0.5%, 1%, or 2% $\text{g-C}_3\text{N}_4$ relative to $\text{BiVO}_4/\text{Fe}_3\text{O}_4$ was introduced into 50 mL of a 10 ppm MB solution. Before illuminating process, the mixture was stirred continuously with no illumination for 30 min to reach adsorption-desorption equilibrium. The degradation experiment was then initiated using blue LED illumination positioned 20 cm from the reaction vessel. Throughout the 210 min reaction period, 5 mL of the suspension was withdrawn at 30 min intervals for subsequent analysis.

Following the identification of the optimum photocatalyst composition, the influence of solution pH on photocatalytic performance was investigated at pH values of 3, 5, 7, 9, and 11 under identical experimental conditions. The pH of the MB solution was adjusted before irradiation by adding 0.1 M NaOH or 0.1 M HCl as required. At the end of each degradation experiment, the BNFC-0.5 photocatalyst was recovered using a permanent magnet, rinsed with distilled water, and dried before being used in the next photocatalytic cycle. The contribution of reactive species to the degradation of MB was examined under the optimum photocatalytic conditions using benzoquinone (BQ) as the superoxide radicals ($\bullet\text{O}_2^-$) scavenger, isopropanol (IPA) as the hydroxyl radicals ($\bullet\text{OH}$) scavenger, and ammonium oxalate (AO) as the hole (h^+) scavenger. The reactive

Table 1. Ternary Composites Synthesized with Different Mass Variations of g-C₃N₄

Weight Percentage g-C ₃ N ₄ (%)	Bi(NO ₃) ₃ ·5H ₂ O (B) (g)	NH ₄ VO ₃ (N) (g)	Fe ₃ O ₄ (F) (g)	g-C ₃ N ₄ (C) (g)	Composite Denotation
0%	4.85	1.1698	0.6460	0	BNFC-0
0.5%	4.85	1.1698	0.6460	0.0162	BNFC-0.5
1%	4.85	1.1698	0.6460	0.0485	BNFC-1
2%	4.85	1.1698	0.6460	0.0971	BNFC-2

**Figure 1.** Schematic Illustration of the Synthesis of the BNFC Composite

species responsible for the greatest decrease in degradation efficiency after the addition of a scavenger was identified as the primary active species involved in the photocatalytic reaction.

2.2.4 The Point of Zero Charge (PZC) of BiVO₄/Fe₃O₄/g-C₃N₄

The point of zero charge (PZC) of the BNFC-0.5 composite was established before evaluating the influence of pH on photocatalytic performance. For this purpose, nine Erlenmeyer flasks were each filled with 20 mL of 0.1 M NaCl solution to serve as the supporting electrolyte. The starting pH of each solution was within the range of 2–10 by carefully adding 0.5 M HCl or 0.5 M NaOH. Afterward, 0.02 g of the composite was added to each flask, and each flask was covered with plastic wrap to reduce solvent loss and prevent external contamination. The suspensions were agitated at 150 rpm for 24 h at room temperature to allow the interaction between the composite surface and the solution to reach equilibrium. Once the contact period was completed, the suspensions were left undisturbed until the solid particles settled. The final pH was then measured using a Thermo Scientific Eutech Expert pH. The change in pH was calculated as the resultant of the initial

and final pH. The PZC was identified as the pH at which no difference between the initial and final pH values was observed, corresponding to a surface with no net electrical charge (Sen et al., 2026).

3. RESULTS AND DISCUSSIONS

3.1 Crystal Structure of BiVO₄/Fe₃O₄/g-C₃N₄

The XRD patterns of the synthesized materials are shown in Figure 2a, while the crystallite sizes and lattice parameters are summarized in Table 2. The diffraction peaks of BiVO₄ observed at 2θ values of 19.0° (011), 28.8° (-121), 30.6° (040), and 34.5° (200), while the calculated lattice parameters (a = 5.194 Å, b = 11.693 Å, and c = 5.103 Å) are consistent with the monoclinic BiVO₄ structure (JCPDS 14-0688), which is widely recognized as the phase exhibiting superior photocatalytic performance compared to other BiVO₄ phases (Qamar et al., 2024). The crystallite size of BiVO₄ was calculated to be 10.1 nm. The diffraction peaks of Fe₃O₄ observed at 2θ = 29.31° (220), 35.73° (311), 44.66° (400), and 57.27° (511) are consistent with the cubic spinel magnetite structure (JCPDS 19-0629) (Wardhani et al., 2023). The diffraction pattern of g-C₃N₄ indicates a hexagonal phase corresponding to JCPDS No.

87-1526 (Lai et al., 2026). A dominant diffraction peak at $2\theta = 27.74^\circ$ is indexed to the (002) plane, which is associated with the layered structure and periodic arrangement of aromatic segments within g-C₃N₄ (Chabib et al., 2025). The crystallite sizes were calculated using the Debye-Scherrer Equation (1):

$$D = \frac{k\lambda}{\beta \cos \theta} \quad (1)$$

In this Equation, D represents the crystallite size, λ refers to the wavelength of the X-ray source, θ corresponds to the Bragg angle, β refers to the full width at half maximum (FWHM) of the diffraction peak, and k is the shape factor with a value of 0.9 (Ayub et al., 2026).

XRD analysis of the BNFC-0.5 sample confirmed the successful synthesis of the composite, as evidenced by the presence of the characteristic diffraction peaks of each pure material while preserving the monoclinic BiVO₄ phase. Furthermore, the absence of additional diffraction peaks indicates that the BNFC-0.5 composite was successfully synthesized without impurity phases (Xu et al., 2026). As shown in Figure 2b, the (002) diffraction peak of g-C₃N₄ shifted from 29.93° to 29.95° after the formation of the BNFC-0.5 composite, resulting in a decrease in d-spacing from 2.983 Å to 2.981 Å, indicating interfacial interaction and lattice distortion caused by heterojunction formation between g-C₃N₄ and the metal oxides. This observation is in accordance with the findings of Permana et al. (2025), described a decrease in the d-spacing of the (002) plane of g-C₃N₄ following Fe₃O₄ incorporation. The reduced interlayer distance was attributed to lattice contraction arising from interfacial interactions between the constituent phases, indicating improved structural coupling within the heterojunction system (Permana et al., 2025). The crystallite size of BNFC-0.5 increased to 15.39 nm, as shown in Table 2, indicating improved crystallinity compared to pure BiVO₄. The increased crystallinity in BNFC-0.5 is consistent with the broadening of the XRD peaks, as reflected in the FWHM values. The larger crystallite size of BNFC-0.5 compared with pristine BiVO₄ and g-C₃N₄ further supports the successful integration of the constituent phases into a ternary composite. The higher crystallinity of the composite is expected to yield a more ordered crystal structure with fewer structural imperfections, which may create favorable conditions for photocatalytic reactions and contribute to improved MB degradation (Wahba, 2024).

3.2 Morphology Characterization of BiVO₄/Fe₃O₄/g-C₃N₄

Figure 3. presents SEM images of BiVO₄, Fe₃O₄, g-C₃N₄, and BNFC-0.5 at a magnification of 10,000×. The particle size distribution histograms of the synthesized materials are shown in Figure 3b, 3d, and 3g. Particle size analysis was performed in ImageJ by randomly measuring approximately 70–80 particles from the SEM images. Gaussian fitting was performed in Origin to visualize the particle-size distribution trends of the synthesized materials. Figure 3a illustrates that the synthesized

pure BiVO₄ displays a flower-like morphology expected to increase the number of available reactive sites (Song et al., 2026), with an average particle size distribution of 92.72 nm with a range of 20–1100 nm, as shown in Figure 3b. SEM image of Fe₃O₄ presented in Figure 3c reveals a flat, flaky morphology. The average particle diameter is roughly 24.16 nm, as shown in Figure 3d. The SEM image of g-C₃N₄ made from melamine shows smooth, layered nanosheets created by stacked g-C₃N₄ sheets, as shown in Figure 3e. These nanosheets can act as anchoring sites for BiVO₄ and Fe₃O₄ in the composite. The lateral size of the g-C₃N₄ ranges from 2 to 6 μm. The EDX results, as previously reported by our group and shown in Table 3, indicate that the synthesized material mainly consists of nitrogen and carbon, thereby confirming the successful preparation of g-C₃N₄ with relatively high purity (Arieveali et al., 2025).

The SEM image of the BNFC-0.5 composite confirms its successful formation with a flower-like morphology and well-dispersed phases, as shown in Figure 3f. The flower-like morphology of the BNFC is in agreement with the findings reported that such a morphology rises the amount of active sites, consequently improves the efficiency of MB removal (Song et al., 2026). Figure 3f also shows the structural integration of BiVO₄, Fe₃O₄, and g-C₃N₄ in the composite system. The layered g-C₃N₄ nanosheets serve as a supporting matrix for BiVO₄ and Fe₃O₄ particles. This observation is consistent with previous reports that the layered structure of g-C₃N₄ can effectively stabilize magnetic particles and improve their dispersion in composite systems (Zhao et al., 2022). The average particle diameter is roughly 86.02 nm, as shown in Figure 3g.

The elemental composition summarized in Table 3 reveals that carbon and nitrogen are the major constituents, supporting the formation of g-C₃N₄. As shown in Table 4, bismuth (71.05%) and vanadium (12.96%) are the predominant elements in the BNFC-0.5 composite, indicating that BiVO₄ is the major phase, consistent with the XRD analysis, which shows a dominant monoclinic BiVO₄ structure. The simultaneous detection of Bi, V, O, Fe, and C further demonstrates the successful incorporation of all constituent components into the ternary composite, which may contribute to the material's improved photocatalytic behavior.

3.3 BET Surface Area Analysis

The BET analysis mainly provided micropore-related parameters, including a micropore volume of 0.003 cm³/g and a micropore area of 16.209 m²/g, indicating relatively low microporosity in the BNFC-0.5 composite, as shown in Figure 4. The t-plot curve showed a slight negative slope, suggesting negligible micropore contribution within the composite structure and indicating that micropore-filling mechanisms did not predominantly govern the adsorption process. This observation is consistent with the relatively low micropore volume and micropore area obtained from the BET analysis, suggesting that the BNFC-0.5 composite is mainly dominated by external surface adsorption and surface interaction mechanisms. The

Table 2. Photocatalyst Material, Crystal Size and Lattice Parameters

Material	Crystallite Size (nm)	Lattice Parameters (Å)		
		A	B	C
BiVO ₄	10.10	5.194	11.693	5.103
Fe ₃ O ₄	17.79	8.397	8.397	8.397
g-C ₃ N ₄	2.76	10.216	10.216	5.971
BNFC-0.5	15.39	8.161	10.676	5.101

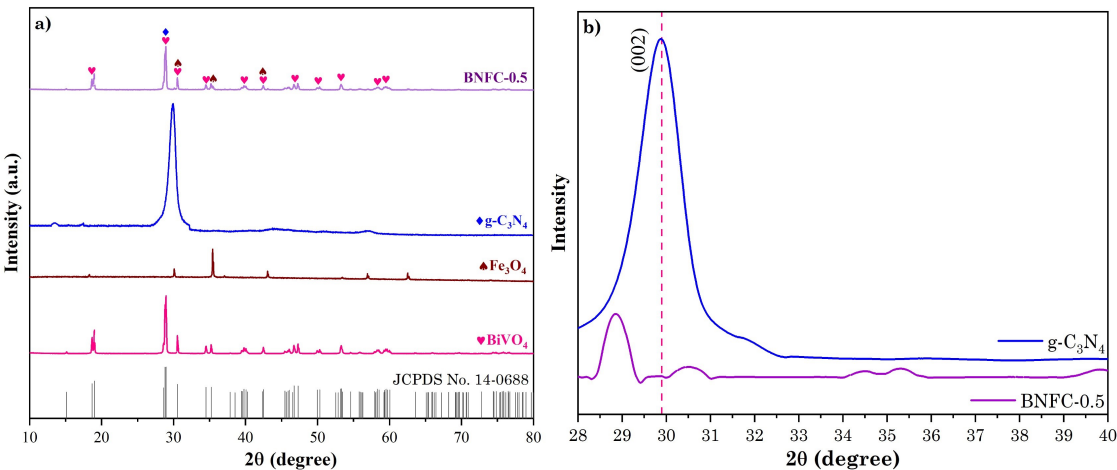


Figure 2. XRD Patterns of BiVO₄, Fe₃O₄, g-C₃N₄, and BNFC-0.5 (a); Changes in the Diffractogram Peaks of g-C₃N₄ in BNFC-0.5 (b)

Table 3. EDX Analysis on g-C₃N₄

Elements	Weight (%)	Atomic (%)
C	40.24	44.61
N	54.59	51.90
O	3.87	3.22
Cu	0.87	0.18
Zn	0.44	0.09

Table 4. EDX Analysis on BNFC-0.5

Elements	Weight (%)	Atomic (%)
Bi	71.05	24.94
V	12.96	18.60
O	5.51	24.67
Fe	6.37	7.76
C	4.11	24.03

limited microporosity may arise from the interfacial assembly of BiVO₄, Fe₃O₄, and g-C₃N₄ within the ternary heterojunction.

Despite the limited microporous characteristics, the composite still exhibited relatively high adsorption performance toward MB. These results suggest that MB adsorption is more likely governed by interactions on the composite’s external surface than by adsorption within micropores. The incorporation of g-C₃N₄ may provide additional adsorption sites, where electrostatic attraction and π - π interactions between the conjugated structure of g-C₃N₄ and the aromatic rings of MB are expected to facilitate dye adsorption (Shahverdizadeh et al., 2025). Furthermore, these adsorption interactions are likely to increase the residence time of MB molecules near the catalyst surface, which may facilitate their subsequent oxidation during photocatalysis.

3.4 Optical Properties and Bandgap Determination

Tauc-plot analysis was performed to determine the maximum absorption edge, as shown in Figure 5a, and the band gap energy of the materials, as shown in Figure 5b, based on the UV-Vis DRS spectra. The absorption edges of BiVO₄, g-C₃N₄, BNFC-0, and BNFC-0.5 were 493 nm, 432 nm, 465 nm, and 512 nm, respectively. Meanwhile, the corresponding band gap energies were 2.51 eV, 2.86 eV, 2.66 eV, and 2.48 eV, respec-

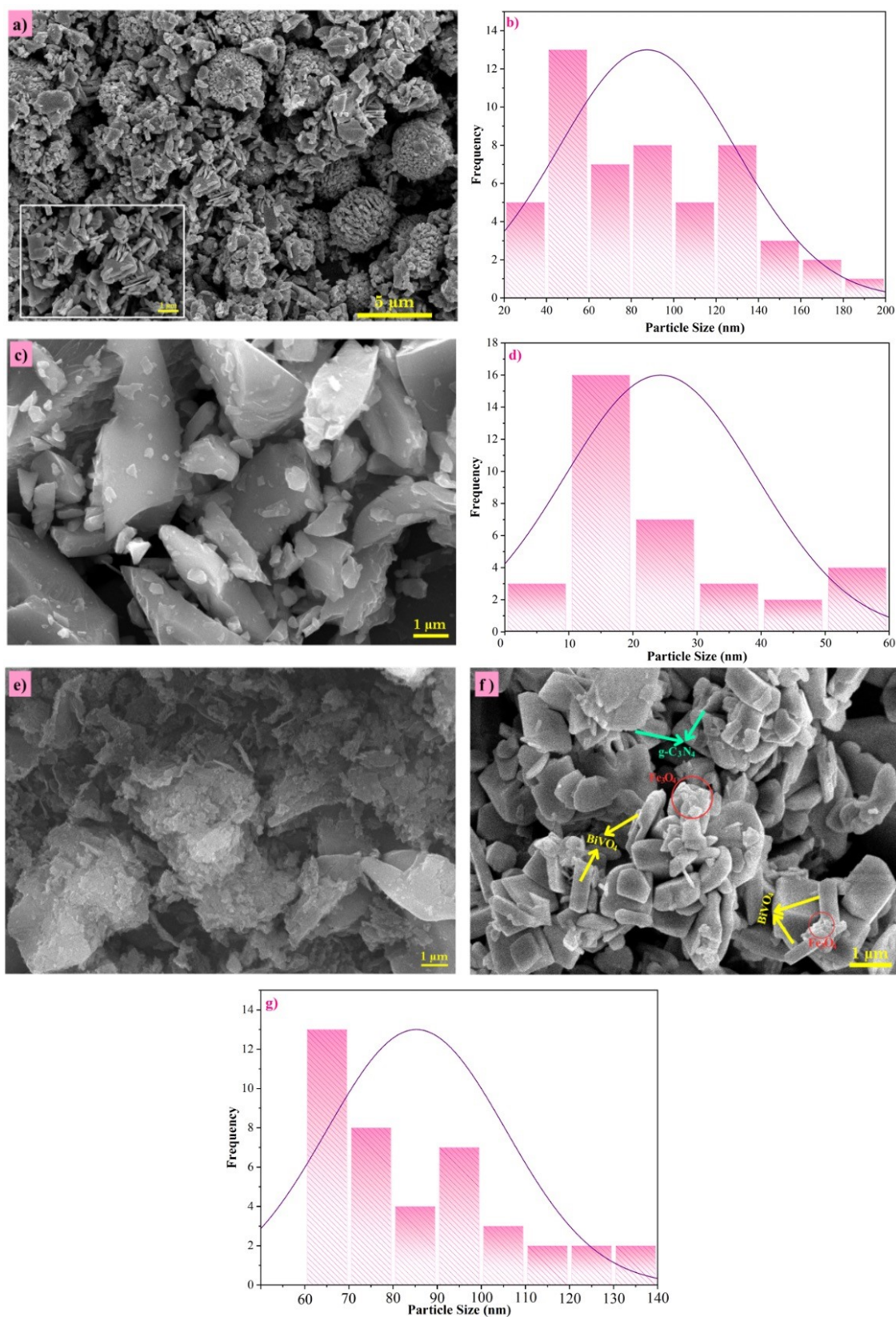


Figure 3. SEM Images of BiVO_4 (a, b), Fe_3O_4 (c, d), $\text{g-C}_3\text{N}_4$ (e), and BNFC-0.5 (f, g); The Additional Magnified SEM Image of BiVO_4 at 10,000 $\times$ Magnification Is Shown in Panel (a).

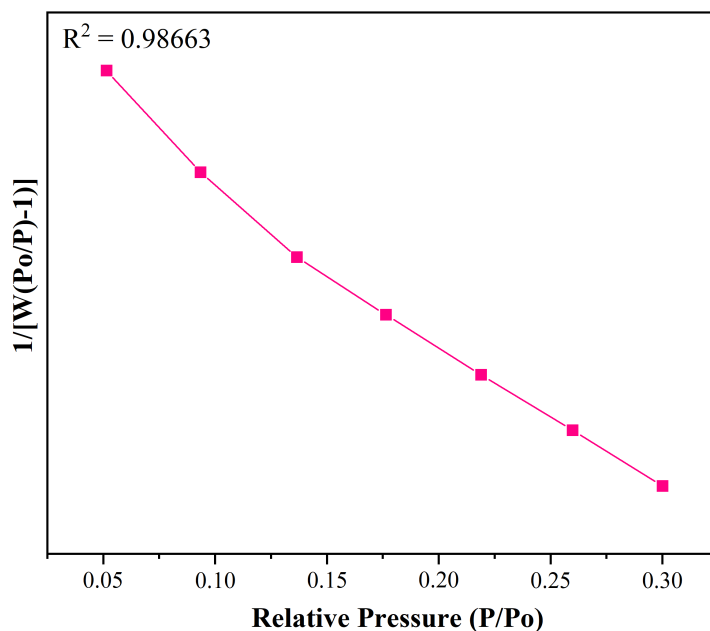


Figure 4. Linear Fit BET Plot of BNFC-0.5

tively. These interfacial interactions further reduced the band gap energy of BNFC-0.5 to 2.48 eV, indicating stronger electronic interactions among BiVO₄, Fe₃O₄, and g-C₃N₄. The synergistic interaction among these components broadens the visible-light response and is proposed to facilitate interfacial charge transfer within the composite system. The formation of a well-integrated interface between BiVO₄, Fe₃O₄, and g-C₃N₄ is meant to alleviate charge transport across the composite. Comparable behavior has also been reported for BiVO₄/g-C₃N₄ systems, where broader visible-light absorption, together with a lower band gap, contributed to better transport of photo-generated charge carriers (Akhtar et al., 2026).

These observations suggest that incorporating BiVO₄, -Fe₃O₄, and g-C₃N₄ into a single composite provides favorable pathways for charge transfer during photocatalysis. The lower band gap energy measured for BNFC-0.5 also indicates that visible-light excitation can occur with less energy input than that required for the individual components. Consequently, a larger fraction of incident visible light can be utilized to initiate photocatalytic reactions, creating conditions that promote the generation of reactive oxygen species (Mancuso et al., 2025). Overall, the combination of broader visible-light harvesting, lower excitation energy, and more favorable charge migration provides a reasonable explanation for the superior photocatalytic activity exhibited by the BNFC-0.5 composite.

To analyze the electronic band structure of the photocatalysts, the positions of the conduction band (CB) and valence band (VB) for g-C₃N₄ and BiVO₄ were determined according

to the calculations described in Equations (2) and (3):

$$E_{CB} = X - E^e - 0.5E_g \quad (2)$$

$$E_{VB} = E_{CB} + E_g \quad (3)$$

In Equations (2) and (3), E_{CB}, E_{VB} represent the conduction band and valence band potentials, respectively, while E_g denotes the band gap energy. E^e corresponds to the free-electron energy on the hydrogen scale, and X refers to the absolute electronegativity of the semiconductor. The X values adopted for BiVO₄ and g-C₃N₄ were 6.16 and 4.67 eV, respectively (Saqib et al., 2025). According to these calculations, the CB and VB potentials of BiVO₄ are 0.29 eV and 2.80 eV, respectively, while those of g-C₃N₄ are -1.2 eV and 1.66 eV, respectively.

3.5 Optimum Mass Variation

The optimal g-C₃N₄ mass fraction in the BNFC composite was determined to identify the composition that provides the highest photocatalytic performance. Composites containing varying g-C₃N₄ mass ratios (0%, 0.5%, 1%, and 2%) were evaluated for their photocatalytic efficiency in degrading MB. As shown in Figure 6, the BNFC-0.5 composite achieved the highest degradation efficiency of 90.56%, indicating the best photodegradation performance among the pure materials and binary composites. The degradation percentage was calculated using Equation (4):

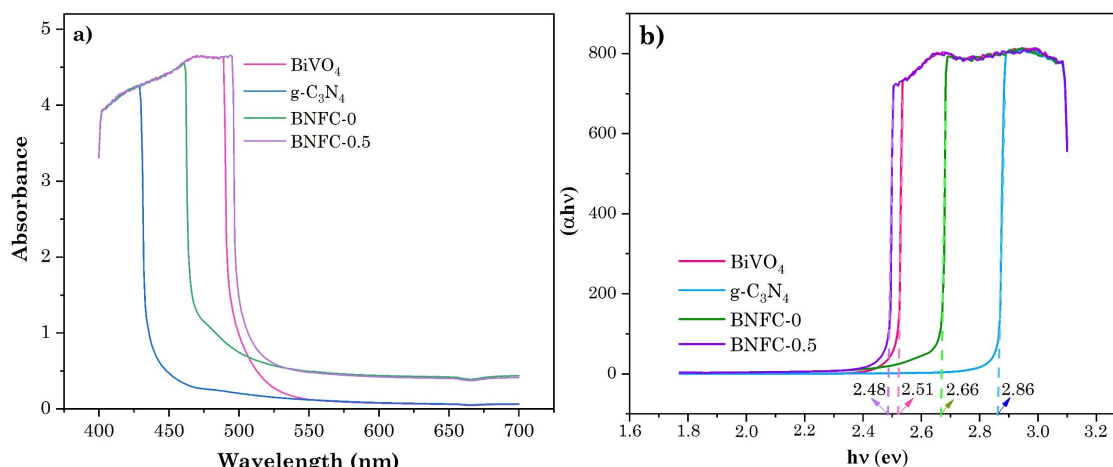


Figure 5. Absorbance Spectra of BiVO₄, g-C₃N₄, BNFC-0, and BNFC-0.5 (a); Band Gap Energy of BiVO₄, g-C₃N₄, BNFC-0, and BNFC-0.5 (b)

$$\text{Degradation}(\%) = \frac{C_0 - C}{C} \times 100\% \quad (4)$$

Where C_0 is the starting concentration at $t = 0$, while C refers to MB concentration at a particular irradiation time (Ahmed et al., 2025). A similar trend was described by Mancuso et al. (2025), stated that increasing the proportion of g-C₃N₄ in a g-C₃N₄/N-TiO₂ composite adversely affected photocatalytic activity. This reduction was associated with poorer light penetration, leaving fewer active sites available for activation during irradiation.

3.6 Point of Zero Charge (PZC) and Optimum pH of BNFC-0.5

The PZC of the BNFC-0.5 ternary composite was determined to be pH 6, and the PZC results are presented in Figure 7a. The composite surface acquires a negative charge when the solution pH exceeds 6, owing to the deprotonation of exterior hydroxyl groups. The pKa of MB is 3.8, which indicates that at pH values greater than the pKa, MB exists as a cation in aqueous solution (Trampuz et al., 2022). Under alkaline conditions above the PZC of BNFC-0.5, the negatively charged catalyst surface attracts positively charged MB molecules through electrostatic forces. The enhanced adsorption is expected to increase the availability of MB at the catalyst surface, contributing to more effective photocatalytic degradation (Zyoud, Zyoud, Zyoud, Nassar, Zyoud, Qamhie, Hajamohideen, and Hilal, 2023). This behavior explains the enhanced degradation performance observed at alkaline conditions. Therefore, controlling the surface charge is crucial for improving dye adsorption and photocatalytic efficiency.

The optimum pH value from the analysis results was pH 9, as shown in Figure 7b. This observation is consistent with the PZC value of BNFC-0.5 (pH 6). Conversely, at pH 3, the lowest degradation efficiency was attributed to the relatively

low concentration of OH⁻ ions under acidic conditions. The limited availability of •OH under these conditions reduces the photocatalytic system's oxidation capacity. This behavior is in agreement with the PZC analysis, which indicates that the surface of BNFC-0.5 carries a positive charge at pH values below 6. Because MB is a cationic dye, electrostatic repulsion between the cationic nature and the positively charged BNFC-0.5 reduces dye adsorption, thereby lowering photocatalytic degradation efficiency (Priyadarshini et al., 2026). In contrast, alkaline conditions provide a higher concentration of OH⁻ ions, which promotes the generation of •OH radicals. The stability of •O₂⁻ is higher in alkaline solutions. In contrast, under acidic conditions, these radicals are readily protonated to form hydroperoxyl radicals (HO₂•), whose oxidation capability is lower (Mammeri et al., 2024). These factors contribute to the enhanced photocatalytic performance observed at pH 9.

3.7 Identification of Optimum Degradation Time

The results of the optimum irradiation time are presented in Figure 8. The optimum irradiation time was investigated at reaction times of 30, 60, 90, 120, 130, 140, 150, 160, 170, 180, and 210 min using the optimum composite (BNFC-0.5) at the optimum pH (9). The findings reveal that the degradation efficiency increases with increasing irradiation time. This trend is attributed to the continuous formation and accumulation of ROS, particularly •OH and •O₂⁻, during prolonged light exposure. Prolonged light exposure enables the photocatalyst to continuously generate photogenerated charge carriers, thereby increasing the availability of reactive species capable of oxidizing MB molecules (Akbar et al., 2026).

The results indicate that effective degradation occurs during the irradiation time range of 120–180 min, as shown in Figure 8a. To determine the precise optimum time, additional experiments were conducted at 10-min intervals within this range, as presented in Figure 8b. The analysis indicates that the optimum irradiation time is 160 min, after which the degradation

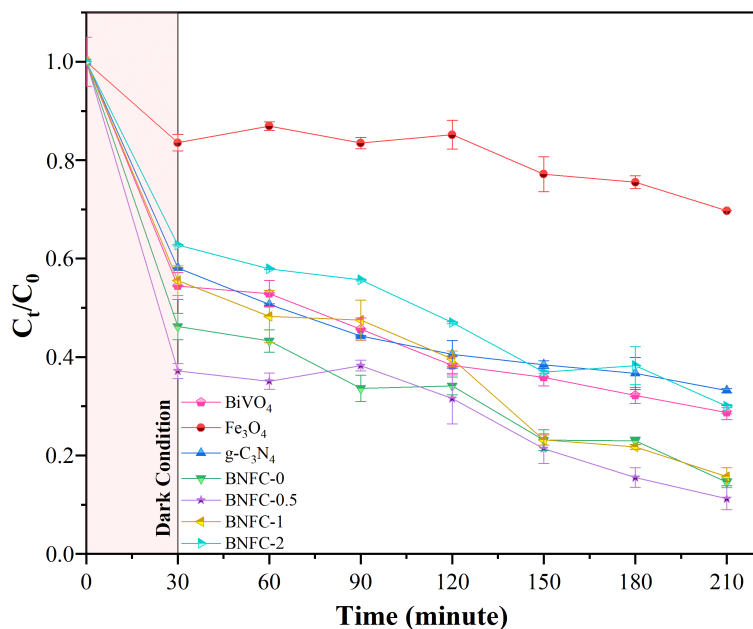


Figure 6. The Effect of Variation of $g\text{-C}_3\text{N}_4$ Mass in BNFC Composites

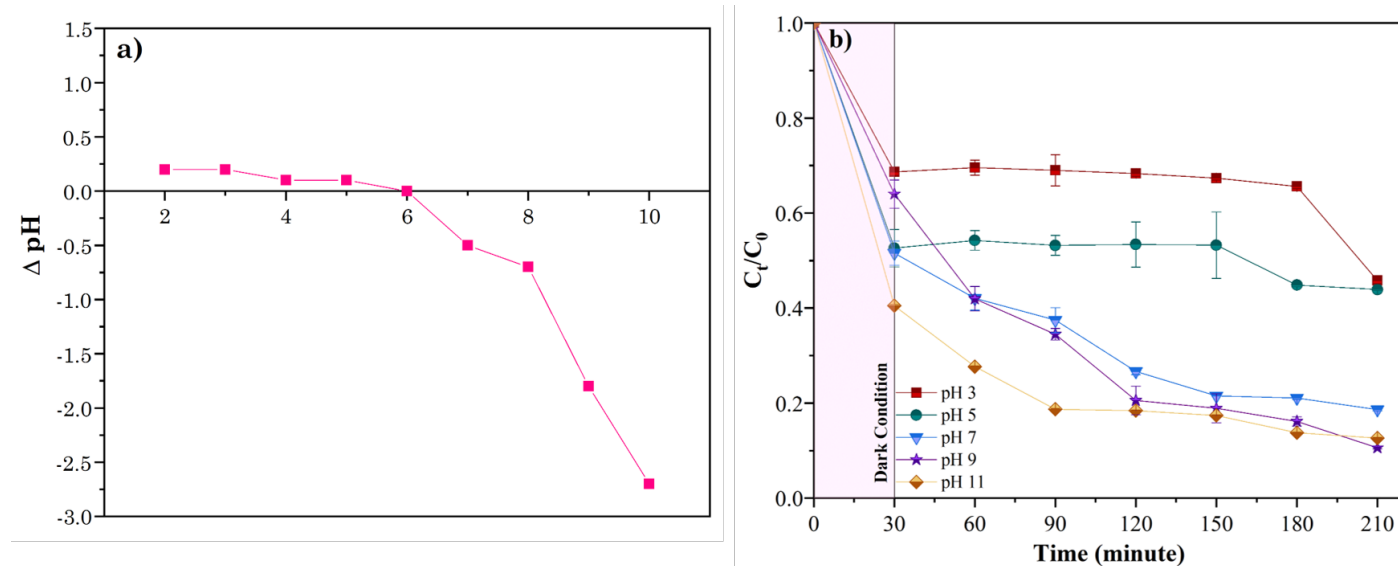


Figure 7. PZC Plot on BNFC-0.5 Composite with pH Drift Method (a); Optimal pH for MB Degradation (b)

performance becomes relatively stable with only a marginal increase. The limited improvement in degradation efficiency after this period is likely due to intermediate degradation products that remain in the reaction system and compete with the parent dye during photocatalysis. As the intermediate products accumulate, they compete with MB for the available reactive species. This competition limits further oxidation of the target

pollutant, resulting in only marginal increases in degradation efficiency at longer irradiation times (Ma et al., 2025).

3.8 Photocatalytic Degradation Kinetic Rates of $\text{BiVO}_4\text{-Fe}_3\text{O}_4/g\text{-C}_3\text{N}_4$

The degradation kinetics of the BNFC-0.5 photocatalyst were evaluated by correlating the initial MB concentration with the

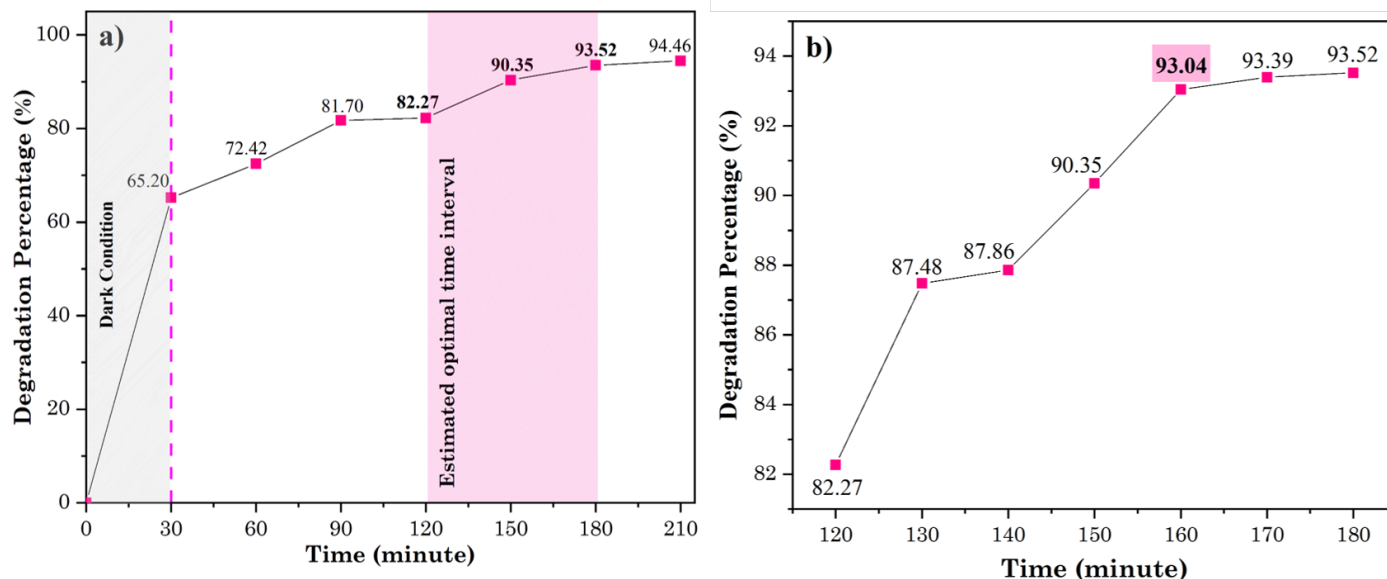


Figure 8. Percentage of Total Degradation Every 30 Minutes (a); Every 10 Minutes (b)

corresponding initial degradation rate, as described by the Langmuir-Hinshelwood (L-H) model, presented in Figure 9. (Arieveali et al., 2026). The high correlation coefficients ($R^2 \geq 0.99$) indicate that the process can be well-fitted by a pseudo-first-order kinetic model based on the Langmuir-Hinshelwood approach (Wahyuni et al., 2024). Furthermore, the reaction rate constant of BNFC-0.5 was found to be 1.691, 6.053, 2.264, 1.243, 1.186, and 1.885 times higher than those of BiVO_4 , Fe_3O_4 , g- C_3N_4 , BNFC-0, BNFC-1, and BNFC-2, respectively. These results indicate that the ternary BNFC-0.5 composite exhibited significantly enhanced photocatalytic activity compared with the single photocatalysts and binary composite systems. These findings are consistent with the UV-Vis DRS results, which demonstrated band-gap narrowing; the XRD analysis, which indicated improved crystallinity and structural characteristics favorable for photocatalytic activity; and the SEM results, which revealed a flower-like morphology expected to increase the photocatalyst's active sites. These synergistic effects collectively enhanced the degradation performance of the BNFC-0.5 composite.

3.9 Mineralization Analysis of MB

TOC analysis determines the mineralization efficiency of MB during the photocatalytic process. The Equation (5) used is as follows:

$$\text{Mineralization}(\%) = \frac{[(\text{TOC})_f - (\text{TOC})_i]}{(\text{TOC})_f} \quad (5)$$

where $(\text{TOC})_i$ and $(\text{TOC})_f$ represent the initial and final TOC concentrations, respectively (Arieveali et al., 2026). The TOC results, shown in Figure 10, indicate that the TOC mineralization efficiency of BNFC-0.5 reached 42.48%, while the

photodegradation efficiency, based on MB concentration removal, reached 93.04%. The difference between photodegradation and TOC mineralization efficiencies indicates that MB molecules were partially decomposed into intermediate organic compounds during the photocatalytic process. Although most of the chromophore structure of MB was successfully degraded, a fraction of organic carbon remained in solution as intermediate products, suggesting that a longer irradiation time is a necessity for a best result (Nandisha et al., 2024).

3.10 Photocatalytic Mechanism Analysis

The degradation mechanism was investigated by identifying the reactive radicals involved in MB photodegradation. Three distinct scavenger solutions were employed in the radical scavenging experiments, such as BQ, AO, and IPA. The degradation efficiency after adding these scavengers is shown in Figure 11. The results reveal that the order of dominant reactive radicals involved in the photodegradation of MB by the BNFC-0.5 composite follows the sequence of $\bullet\text{OH} > \text{h}^+ > \bullet\text{O}_2^-$. Among the scavengers examined, isopropanol caused the largest decrease in degradation efficiency, reaching 25.58%. This result suggests that hydroxyl radicals ($\bullet\text{OH}$) were the prominent active species involved in MB degradation. The observation is also supported by the PZC measurement, which showed that the BNFC-0.5 surface has a point of zero charge at pH 6. At pH values above this point, the increased availability of OH^- ions favors the generation of $\bullet\text{OH}$ radicals via oxidation by photogenerated holes (h^+), thereby improving MB degradation (Mottammal et al., 2026). These findings are also consistent with the experimental results showing that the optimum photocatalytic activity was achieved at pH 9.

The photocatalytic degradation of MB over the BNFC-0.5 composite is proposed to proceed via a plausible Z-scheme

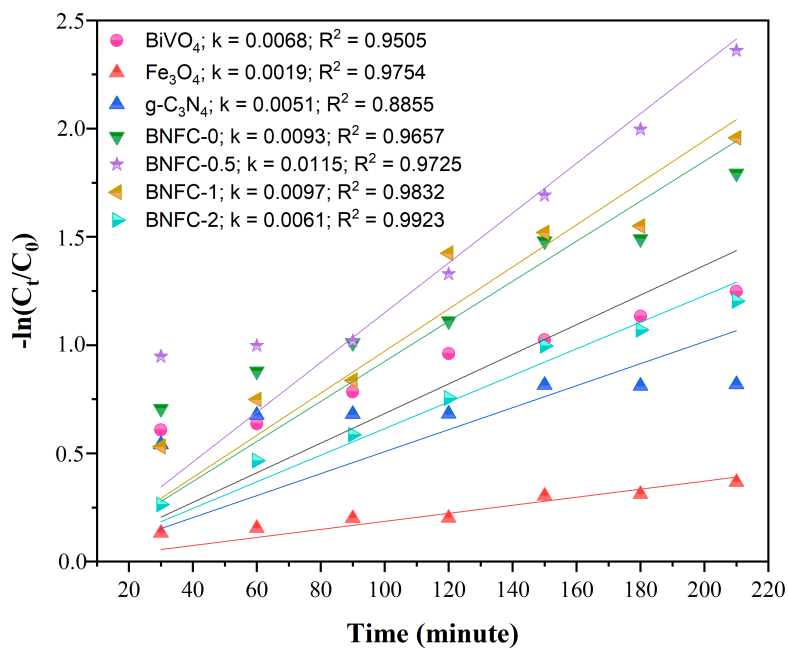


Figure 9. Kinetic Curve of Langmuir-Hinshelwood

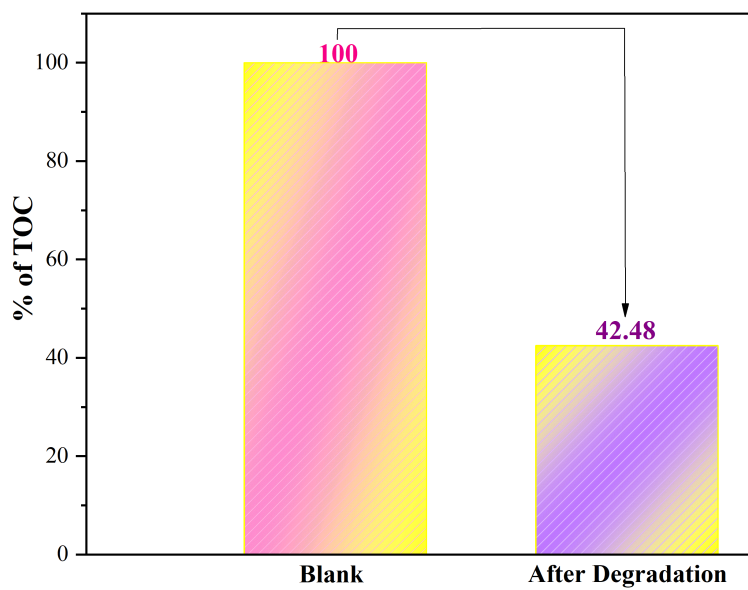


Figure 10. TOC Removal of MB

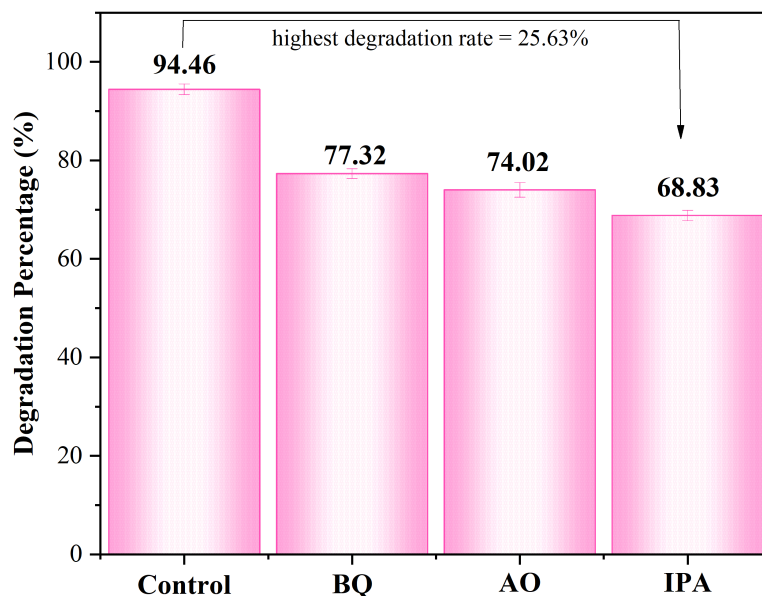


Figure 11. Effect of Scavengers in the Photodegradation Process by BNFC-0.5 Under Optimal Condition

heterojunction mechanism, supported by band-structure considerations and scavenger experiments. The dominant role of $\bullet\text{OH}$ radicals, followed by holes and superoxide radicals, suggests that oxidative degradation pathways are mainly governed by strong oxidation reactions occurring on the BiVO_4 surface under visible-light irradiation. The energy-band alignment, together with the scavenger test, provides a basis for proposing a Z-scheme charge-transfer pathway for the BNFC-0.5 composite during MB degradation, as depicted in Figure 12. When exposed to visible light, both BiVO_4 and $\text{g-C}_3\text{N}_4$ absorb photons, generating electrons in the conduction band while leaving holes in the valence band of each semiconductor. The $\text{g-C}_3\text{N}_4$ material provides electrons with sufficient reducing power to transform dissolved oxygen into superoxide radicals ($\bullet\text{O}_2^-$) on account of its conduction band potential (-1.2 eV). In contrast, BiVO_4 has a conduction band position at 0.29 eV, which is thermodynamically unfavorable for generating $\bullet\text{O}_2^-$, it does not contribute to the formation of superoxide radicals. In the proposed charge-transfer process, electrons generated in the conduction band of BiVO_4 are transferred through Fe_3O_4 and combine with holes located in the valence band of $\text{g-C}_3\text{N}_4$, leaving the remaining electrons and holes with sufficiently strong redox capability to participate in photocatalytic reactions. Consequently, the electrons retained in the conduction band of $\text{g-C}_3\text{N}_4$ interact with dissolved oxygen to produce superoxide radicals ($\bullet\text{O}_2^-$), whereas the holes remaining in the valence band of BiVO_4 oxidize water molecules or hydroxide ions to generate hydroxyl radicals ($\bullet\text{OH}$). Because the valence band

potential of BiVO_4 (2.80 eV) is more positive than the potential required for $\bullet\text{OH}$ formation from $\text{H}_2\text{O}/\text{OH}^-$ (2.68 eV), this oxidation process is thermodynamically feasible. The predominance of $\bullet\text{OH}$ radicals inferred from this mechanism agrees with the scavenger experiment, where the addition of isopropanol produced the largest decrease in MB degradation efficiency.

Furthermore, the continuous recombination of electrons from BiVO_4 via Fe_3O_4 with holes in $\text{g-C}_3\text{N}_4$ promotes hole accumulation in the BiVO_4 valence band, thereby enhancing its ability to oxidize MB molecules directly. In addition, Fe_3O_4 imparts magnetic properties to the composite, enabling efficient separation of the BNFC-0.5 photocatalyst from solution for reuse in degradation. Overall, this mechanism is consistent with previously reported Z-scheme ternary photocatalysts, including $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{g-C}_3\text{N}_4$ systems, where spatial charge separation and preservation of strong redox potentials are key to enhanced photocatalytic performance (Madima et al., 2023).

3.11 Reusability

The reusability and magnetic separation performance of the BNFC-0.5 composite are presented in Figure 13a. The reusability test was conducted over four consecutive cycles, each with a degradation time of 160 minutes. The results demonstrate that the photocatalytic activity of BNFC-0.5 decreases only slightly after repeated use. The degradation efficiencies for each cycle were 90.69%, 88.47%, 82.97%, and 79.32%, respectively, indicating that the performance decline is relatively minor. This

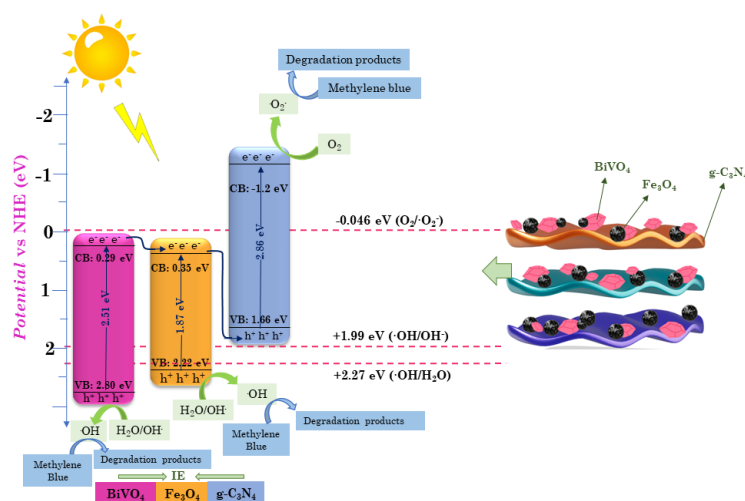


Figure 12. Z-Scheme Mechanism of MB Degradation Using BNFC-0.5

slight decline suggests that the structural integrity and active sites of the photocatalyst are well maintained during repeated cycles, demonstrating the composite's good stability (Taravati et al., 2025). These results confirm that the BNFC-0.5 ternary composite exhibits excellent structural and chemical stability, as well as high reusability. Additionally, the external magnetic field generated by Fe_3O_4 enables efficient separation of the BNFC-0.5 composite from waste solutions, thereby supporting the recovery and reuse of photocatalysts in practical applications. These findings confirm that incorporating Fe_3O_4 not only enhances photocatalytic performance but also improves catalyst recovery and recyclability. This magnetic property, attributed to Fe_3O_4 , enhances the applicability of the composite by simplifying post-reaction separation.

The structural stability of the BNFC-0.5 composite was further evaluated based on the diffractogram of BNFC-0.5 after degradation, as shown in Figure 13b. The diffraction peaks at $2\theta = 30.14^\circ$ and 43.08° exhibited a substantial decrease in intensity and became indistinguishable after the degradation process. This phenomenon was caused by partial modification of the surface and the adsorption of reaction intermediates on the photocatalyst surface during the photocatalytic process, which slightly reduced the crystallinity of certain domains without significantly altering the overall crystal structure (Arieveali et al., 2026). However, nearly all diffraction peaks were identical to those of BNFC-0.5 before degradation. This indicates good crystal structure stability of the BNFC-0.5 composite during the photocatalytic reaction (Sabariselvan et al., 2025). This structural stability indicates that the degradation performance is maintained even after prior use in photocatalytic processes. This demonstrates its great potential for the remediation of dye wastewater in real-world applications.

Table 5. compares the photocatalytic performance of BNFC-0.5 with previously reported BiVO_4 , Fe_3O_4 , and $\text{g-C}_3\text{N}_4$ -

based photocatalysts for MB degradation. The BNFC-0.5 composite achieved a degradation efficiency of 93.04% under visible-light irradiation within 160 minutes, which is comparable to several recently reported ternary heterojunction photocatalysts. Although some photocatalysts exhibited slightly higher degradation efficiencies or shorter degradation times, several required UV irradiations or showed lower reusability. Compared with $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{g-C}_3\text{N}_4$ and $\text{Fe}_3\text{O}_4/\text{TiO}_2/\text{ZnO}$ composites, BNFC-0.5 demonstrated superior visible-light activity, which is advantageous for environmentally friendly and sustainable photocatalytic applications. After four consecutive photocatalytic cycles, BNFC-0.5 retained 79.32% of its initial degradation efficiency, demonstrating consistent performance during repeated use. This value is comparable to, and in some cases exceeds, those reported for other magnetically recoverable photocatalysts. The improved photocatalytic behavior is imputed to the integration of BiVO_4 , Fe_3O_4 , and $\text{g-C}_3\text{N}_4$ into a single composite, which enables efficacious utilization of visible light and provides favorable pathways for the transfer of photogenerated charge carriers. In addition, Fe_3O_4 provided magnetic recoverability while maintaining stable photocatalytic performance during repeated use, indicating the potential of BNFC-0.5 for practical wastewater treatment applications.

3.12 Magnetic Properties

The magnetic properties of the synthesized BNFC-0.5 composite were evaluated using a VSM (Oxford 1.2H) and compared with pure Fe_3O_4 , as shown in Figure 14. and Table 6. The saturation magnetization (M_s) value of BNFC-0.5 was 15.93 emu/g, indicating a significant magnetic response due to Fe_3O_4 within the $\text{g-C}_3\text{N}_4$ matrix and BiVO_4 . However, this value was lower than that of pure Fe_3O_4 (93.27 emu/g), indicating the influence of the nonmagnetic nature of the $\text{g-C}_3\text{N}_4$ matrix and BiVO_4 . The coercivity (HC) of BNFC-0.5 was

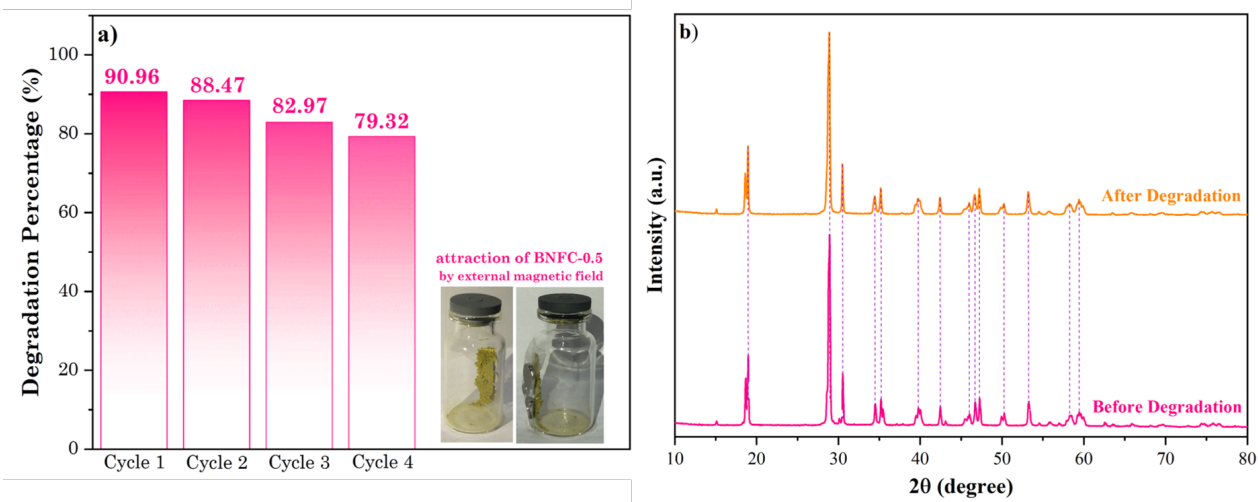


Figure 13. Reusability Performance Evaluation of BNFC-0.5 (a); and XRD Patterns of BNFC-0.5 After Degradation (b)

Table 5. Comparison of BiVO₄, Fe₃O₄, and g-C₃N₄-Based Photocatalysts for MB Degradation

Photocatalysts	Light source	Time (minute)	Degradation percentage (%)	Reusability (repetition, %)	References
Fe ₃ O ₄ /TiO ₂ /g-C ₃ N ₄	UV	80	95	5x (88)	(Madima et al., 2023)
C/Fe ₃ O ₄ /Bi ₂ O ₃	Visible	90	94	4x (90)	(Saqib et al., 2025)
Fe ₃ O ₄ /TiO ₂ /ZnO	UV	60	80.04	3x (67.49)	(Wulandari et al., 2025)
g-C ₃ N ₄ /Fe ₃ O ₄	Visible	120	90	3x (85)	(Avilés-Monreal et al., 2026)
BiVO ₄ /g-C ₃ N ₄	Visible	150	91	-	(Haryadinaru et al., 2025)
g-C ₃ N ₄ /BiVO ₄ /GQDs	Visible	150	94.81	-	(Arieveali et al., 2025)
BiVO ₄ /FeVO ₄	Visible	60	91	-	(Ge et al., 2025)
g-C ₃ N ₄ /CdS/BiVO ₄	Visible	120	94.05	-	(Ranjith et al., 2023)
BiVO ₄ /Fe ₃ O ₄ /g-C ₃ N ₄	Visible	160	93.04	4x (79.32)	This work.

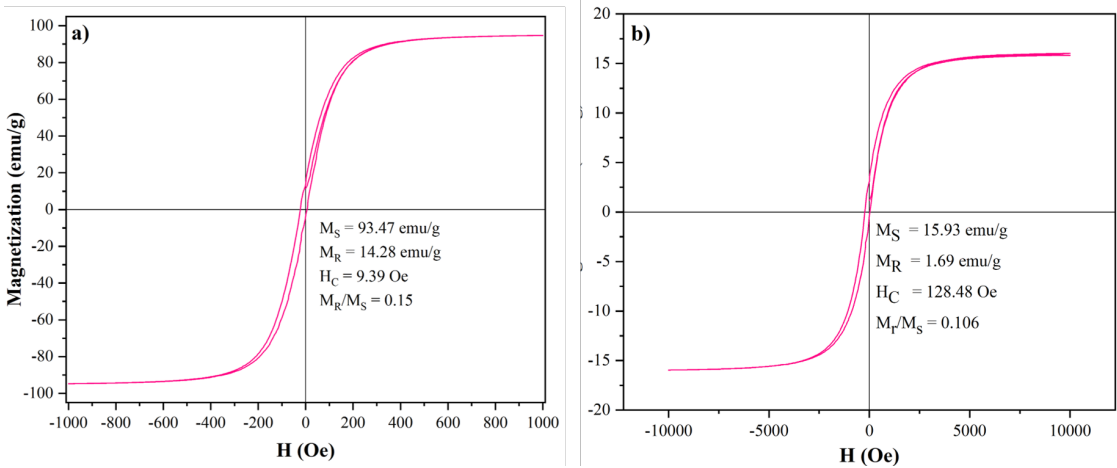


Figure 14. Magnetic Hysteresis (M–H) Loops of Fe₃O₄ (a); and BNFC-0.5 (b)

128.48 G (Oe), indicating that the composite exhibits soft magnetic behavior with relatively low demagnetization resistance. An MR value of 1.69 emu/g was obtained for the BNFC-0.5 composite, indicating that a portion of its magnetization was retained after the external magnetic field had been removed. The substantial difference between the MS and MR values suggests limited magnetic hysteresis and low remanence, both

of which are generally associated with soft ferromagnetic or superparamagnetic-like behavior. Overall, the magnetic behavior of the BNFC-0.5 composite demonstrates good agreement with previously reported g-C₃N₄/Fe₃O₄/PANI ternary composites, confirming that the incorporation of Fe₃O₄ provides sufficient magnetic responsiveness for efficient photocatalyst recovery and reuse after the photocatalytic process (Lai et al.,

Table 6. Magnetic Properties of Fe₃O₄ and BNFC-0.5 Composite

Sample	MS (emu/g)	MR (emu/g)	HC (Oe)	MR/MS
Fe ₃ O ₄	93.47	14.28	9.39	0.151
BNFC-0.5	15.93	1.69	128.48	0.106

2026). These VSM results are also consistent with the reuse performance of BNFC-0.5 over four cycles, maintaining a degradation efficiency of 79.32%, indicating that the composite maintains adequate magnetic recovery capability and stability during repeated use.

4. CONCLUSIONS

This study demonstrates that incorporating BiVO₄, Fe₃O₄, and g-C₃N₄ into a ternary composite provides an effective approach to developing a visible-light-responsive photocatalyst with magnetic recovery capability. Among the synthesized composites, BNFC-0.5 exhibited the best photocatalytic performance, achieving 93.04% degradation under the optimum conditions of pH 9 at 160 minutes irradiation, together with a TOC mineralization efficiency of 42.48%. the BNFC-0.5 composite retained 79.32% degradation efficiency after four reuse cycles. The findings show that optimizing the g-C₃N₄ content is relevant for attaining balanced optical and magnetic properties, thereby improving photocatalytic performance and enabling convenient catalyst separation and reuse. These results provide further understanding of the multifunctional heterojunction photocatalysis by proposing a Z-scheme heterojunction and showcasing the need for compositional control for achieving both high degradation efficiency and operational practicality. Therefore, the developed BNFC-0.5 composite represents a promising candidate for advanced wastewater treatment process. Future studies should evaluate the photocatalyst in real wastewater systems, investigate its long-term stability over extended reuse cycles, and explore the degradation behavior of a wider range of organic contaminants.

5. ACKNOWLEDGEMENT

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