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Towards the Development of a Z-Scheme FeOx/g-C₃N₄ Thin Film and Perspectives for Ciprofloxacin Visible Light-Driven Photocatalytic Degradation

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Abstract: Thermally synthesized graphitic carbon nitride (g-C₃N₄) over pulsed laser deposition (PLD) produced urchin-like iron oxide (FeOx) thin films were fabricated via in situ and ex situ processes. Materials characterisation revealed the formation of the graphitic allotrope of C₃N₄ and a bandgap E_g for the combined FeOx/g-C₃N₄ of 1.87 and 1.95 eV for each of the different fabrication strategies. The in situ method permitted to develop a novel petal-like morphology, whereas for the ex situ method, a morphological mixture between FeOx bulk and g-C₃N₄ was observed. Given the improved optical and morphological properties of the in situ film, it was employed as a proof of concept for the direct photocatalysis and photo-Fenton removal of ciprofloxacin antibiotic (CIP) under visible light irradiation. Improved photocatalytic activity (rate constant $k = 8.28 \times 10^{-4} \text{ min}^{-1}$) was observed, with further enhancement under photo-Fenton conditions ($k = 2.6 \times 10^{-3} \text{ min}^{-1}$), in comparison with FeOx + H₂O₂ ($k = 1.6 \times 10^{-3} \text{ min}^{-1}$) and H₂O₂ only ($k = 1.3 \times 10^{-4} \text{ min}^{-1}$). These effects demonstrate the in situ methodology as a viable route to obtain working heterojunctions for solar photocatalysis in thin-film materials, rather than the more common powder materials.

Keywords: FeOx/g-C₃N₄ thin films; petal-like morphologies; Z-scheme; visible light photocatalysis; ciprofloxacin degradation

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1. Introduction

Direct Z-scheme photocatalysis mechanisms, obtained by combining two different photocatalysts (PC), have been proven to be a promising option for enhancing photocatalytic reactions efficiency [1].

In this configuration, inspired by the study of natural photosynthesis, photogenerated electrons in the conduction band (CB) of a PC I can recombine with photogenerated holes in the valence band (VB) of a PC II: this results in a charge-separated state where holes are left on the VB of PC I and electrons on the CB of PC II, separated in space. This inhibits recombination, thus enhancing lifetimes and boosting the yield of redox processes employing them. Z-schemes can be implemented using two semiconductors with opportunely aligned band edges and offers the possibility of using materials with different bandgaps, with a double advantage: (1) materials that are good oxidants but poor reductants can be used as PC I and the reverse can be used for PC II, thus maximizing the activity of their redox potentials; and (2) a broader portion of sunlight spectrum can be exploited.

For these reasons, Z-schemes are increasingly popular in photoactive materials and are increasingly studied for a variety of applications, from water splitting to wastewater remediation [2,3].

Graphitic carbon nitride (g-C₃N₄)-based materials recently attracted great attention due to, among other things, useful optical properties, high chemical stability, and ease of fabrication [4]. g-C₃N₄-based materials could also be used as Fenton-like catalysts, adsorbents, disinfectants, and membrane materials [5–7]. Despite these advantages, g-C₃N₄ also has significant drawbacks, such as poor UV–visible absorption (<450 nm), low surface area, and fast recombination kinetics for photogenerated electron–hole couples, limiting its photocatalytic performance.

Different methodologies for modifying g-C₃N₄ have been investigated in order to improve its performance, for example by doping g-C₃N₄ with different elements: TiO₂ [8–12], Cu [13], SiC [14], Ag [15,16], ZnO [17], graphitized polyacrylonitrile [18], CdO [19], and WO₃ [20]. However, most of these dopings comprise nanomaterials in powdered form and are used for colloidal photocatalysis.

Much less investigated is the possibility of utilizing g-C₃N₄ (either alone or in composites) as thin films over substrate surfaces, for example FTO [21–24]. In water purification applications, the use of colloidal suspensions still represents the main research field due to the available high surface areas. However, the recovery of the material, after use, constitutes an additional problem [25]. From an industrial perspective, working with immobilized photocatalysts, such as thin films, allows the facile removal at the end of the process and displays enhanced compatibility with flow reactor installations [26,27]. On the other hand, the application of Z-schemes or other useful heterojunction-based design principles is quite straightforward and well established for nanopowders but much more difficult for thin-films. Indeed, for such a material to be effective in photocatalysis, both the components need to have a solid–liquid interface at which redox reactions with substrates can occur, and this is not possible with the layered composites generally obtained with most thin-film fabrication methods.

In photocatalysis, g-C₃N₄ composites have been recently investigated for the degradation of emerging pharmaceutical contaminants (like sulphonamides, acyclovir) as well as of pesticides [28–33]. Only a few papers deal with the synthesis of FeO_x/C₃N₄ composites for oxidation processes, water splitting, electro-catalysis, dye degradation, or artificial photosynthesis [34–36]. Note that both materials are industrially scalable, economically viable, abundant (in the case of iron oxides), and environmentally compatible [37], so that a composite, based on these materials, which incorporates heterojunction effects into a thin-film design would be a breakthrough towards application. Regarding pharmaceutical contaminants specifically, CIP, a fluoroquinolone antibiotic used in medicine and veterinary practice both, is of particular interest: it is one of the most widely used antibiotics worldwide and standard wastewater treatments are largely ineffective for its removal, leading to its frequent detection in surface waters in many regions. It is thus considered a potential source of antimicrobial resistance (AMR), an increasingly severe threat to public health [38]. Note that, while the final target of solar-wastewater treatments is generally the complete removal of pollutants via mineralisation, avoiding AMR in principle only requires the inactivation of antibiotic residues in water instead [39]. To this end, solar-driven photocatalysis would be a potentially cost-effective, high-efficiency treatment process.

In this paper, we investigate the production of Z-scheme composite thin films based on the combination of pulsed laser deposition (PLD)-produced urchin-like iron oxide (FeO_x) nanostructured film with g-C₃N₄ to be employed for ciprofloxacin (CIP) degradation. The urchin-like FeO_x was recently developed in our lab and has been selected as a platform for the composite synthesis because it has good solar spectrum compatibility, with an energy bandgap $E_g = 2.2$ eV; consists of hierarchical structures, which are beneficial for applications requiring high surface area [40,41]; and finally, it is photo-Fenton active [42,43]. Two different strategies were used to prepare FeO_x/g-C₃N₄

composite films. In the first case, we grew the petal-like g-C₃N₄ over iron urchins by directly drop-casting the melamine solution followed by thermal treatment (in situ). In the second case, previously synthesized g-C₃N₄ powder was spin-coated over iron urchins (ex situ). The photocatalytic performance of the coatings has been evaluated via the degradation of ciprofloxacin (CIP) under visible light. CIP is indeed an important emerging contaminant, but at the same time it is well-studied, its degradation mechanism well reported, and it can easily be followed by simple UV–visible methods; therefore, it can be used to evaluate and tune the performances of our new materials [44–49].

2. Materials and Methods

2.1. Materials and Reagents

Starting elements were metallic iron powder (Ventron GmbH (Karlsruhe, Germany), purity 97%, particle size mesh 325, 56 g/mol), boric acid (H₃BO₃ Sigma-Aldrich (St. Louis, MO, USA) BioXtra, purity > 99.5%, 61.83 g/mol), and melamine (C₃H₆N₆, Sigma-Aldrich, purity > 99%, 126.12 g/mol). Ethanol absolute (VWR, purity 97%, 46.08 g/mol) was used as a dispersing agent for melamine and synthesized g-C₃N₄ powder. Ciprofloxacin (C₁₇H₁₈FN₃O₃, Standard PHR1044 Sigma-Aldrich, purity 99%, 385.82 g/mol) was employed to test the efficiency of photocatalysis. H₂O₂ solution (Merck (Rahway, NJ, USA), EMSURE ISO, concentration 30%, 34.01 g/mol) was employed in the photo-Fenton reactions.

2.2. Synthesis of Iron Oxide Urchins

Urchin-like FeOx nanostructured thin films were produced via PLD following the protocol and apparatus published elsewhere [40,50]. Briefly, the films were obtained using a KrF Lambda Physik excimer laser with a 248 nm wavelength, 25 ns pulse duration, and 20 Hz repetition rate. Targets were prepared as pellets of cold-pressed iron and H₃BO₃-mixed powders (1:1 weight). The deposition of films was carried out on both Si slides (for the purpose of characterisation) and glass slides (75 mm × 26 mm) in O₂ atmosphere (4.5 Pa) at room temperature by keeping them at distance of 4.5 cm from the target. During the deposition, a laser fluence of 3 J/cm² was applied using optical focusing, and 10,000 laser pulses were used for each single substrate glass slide. The prepared films were thermally annealed at 550 °C for 4 h in air atmosphere with a heating rate of 5 °C/min. Deposited films weight was measured using a balance with 10^{−5} g resolution.

2.3. Synthesis of g-C₃N₄ Powder

Melamine was used as the precursor for g-C₃N₄ synthesis. A total of 10 g of melamine powder was added into a porcelain crucible (200 mL) with a closed cap. Before the synthesis, the porcelain crucible was well polished with an abrasive sheet. In the synthesis process, the crucible containing melamine was heated inside a muffle furnace at 550 °C for 4 h with the heating rate of 9 °C/min [51]. This protocol was used to produce bulk g-C₃N₄ powder for characterisation and as part of the process to produce ex situ film.

2.4. Preparation of FeOx/g-C₃N₄ Composite Thin Films

The FeOx/g-C₃N₄ composite materials were prepared by employing the iron oxide urchin film described in Section 2.2 as a support for the g-C₃N₄, following two distinct procedures as described below and schematically presented in Figure 1:

- (a) The g-C₃N₄ powder was synthesized ex situ by thermally heating melamine for 4 h (protocol from Section 2.3). The synthesized g-C₃N₄ was dispersed in ethanol with concentration of 40 mg/mL. The prepared suspension was spin-coated on top of the iron urchins with a rotational speed of 800 rpm for 60 s. The composite material was dried at 60 °C for 4 h to evaporate the extra solvent. The final composite sample is referred to from here onwards as (FeOx/g-C₃N₄)*ex*.

- (b) Starting from melamine, g-C₃N₄ was synthesized in situ on the surface of iron oxide urchin. Specifically, the melamine powder was dispersed in ethanol with a concentration of 100 mg/mL. The prepared suspension was used to spread a controlled amount of melamine precursor on top of the iron urchin film via the drop-casting method. Subsequently, films were heated in a muffle furnace at 550 °C for 1 h to obtain the g-C₃N₄ on top of the iron oxide urchins. The prepared composite is referred to from here onwards as (FeOx/g-C₃N₄)*in*.

Here, we selected 4 h and 1 h durations of annealing for ex situ and in situ methods, respectively, based on the optimisation described in the Supplementary Materials (Section S1).

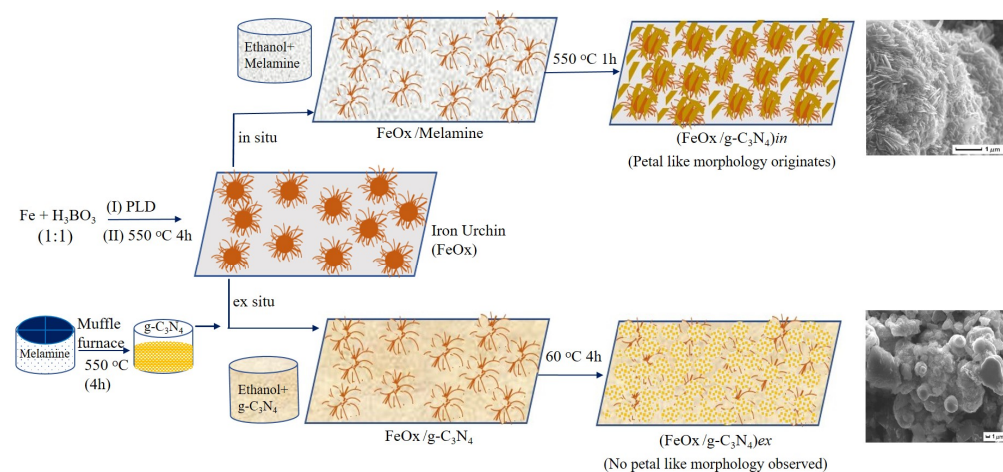


Figure 1. Schematic showing the synthesis of iron urchin (FeOx), g-C₃N₄, and FeOx/g-C₃N₄ composites via different procedures.

2.5. Materials Characterisation

The properties of the obtained materials were investigated via different characterisation techniques. A LabRAM Aramis Jobin-Yvon Horiba μ -Raman equipped with a He-Ne laser source (785 nm) was used for Raman spectroscopy measurements. FT-IR was performed using a JASCO model 4600 instrument (Easton, PA, USA). Grazing incidence XRD (GIXRD) was employed to analyse the crystallinity of samples using a X'Pert Pro diffractometer, working with the Cu K α radiation. A field emission scanning electron microscope (FEG-SEM, JSM-7001F, JEOL (Tokyo, Japan)) equipped with an Energy-Dispersive X-ray Spectroscopy (EDXS-INCA PentaFETx3, Oxford Instruments (Abingdon, UK)) analyser was used to examine morphology and composition, whereas TEM analysis was performed in order to add structural information at a microscopic scale (S/TEM TALOS F200S, ThermoFisher, Waltham, MA, USA). UV and visible (UV-Vis) absorption spectra were measured using a VARIAN Cary 5000 UV-Vis-NIR spectrophotometer over a wavelength range of 200 to 800 nm. The Kubelka–Munk function (Equation (1)) and the Tauc equation were used to evaluate the direct bandgap of the synthesized materials:

$$F(R) = \frac{(1 - R)^2}{2R} \quad (1)$$

where R is the reflectance of the sample.

The Tauc equation for direct electronic transitions is described in Equation (2):

$$(ah\nu)^2 = A(h\nu - E_g) \quad (1)$$

where a is the optical absorption coefficient; $h\nu$ is the incident photon energy in eV; A is the material-dependent absorption constant; and E_g is the energy bandgap.

X-ray photoemission spectroscopy (XPS) measurements were performed on the thin film coatings to understand the surface chemical states of the elements. The X-ray source was a monochromatized Al K α (1486.6 eV) source, and the spectra were collected from an electrostatic hemispherical electron energy analyser with $\pm 8^\circ$ of acceptance angle. The X-ray beam incidence was at an angle of 45° on the surface of the samples and all spectra were acquired in normal emission conditions with an initial base pressure of 2×10^{-9} mbar. The calibration of the data was performed using the C 1 s native peak present on the surface of the samples.

2.6. Photocatalysis Experiments: Degradation of Ciprofloxacin

In a typical experiment, the photocatalyst film was positioned in the centre of a borosilicate glass beaker and immersed in an aqueous solution (50 mL) containing CIP ($C_0 = 10$ ppm) on. The beaker was covered with aluminium foil and kept in the dark for 30 min while stirring (150 rpm) to achieve adsorption–desorption equilibrium. After 30 min of initial dark, the foil was removed and the beaker was irradiated for 180 min. When required, H_2O_2 was added to the starting solution to reach a (5×10^{-4} M) concentration. Aliquots (1 mL) of irradiated solution were taken at fixed time intervals and UV–Vis spectra were recorded to evaluate the extent of CIP disappearance. The absorbance values at $\lambda_{max} = 272$ nm were collected and the degradation of CIP was reported as:

$$\text{Degradation efficiency (\%)} = \left(\frac{C_0 - C_t}{C_0} \right) \times 100 = \left(\frac{A_0 - A_t}{A_0} \right) \times 100 \quad (2)$$

where C_0 and A_0 are the starting molar concentration and absorbance of CIP while C_t and A_t are the molar concentration and absorbance of CIP at time t . Control experiments were carried out by irradiating the starting solution of CIP in the absence of any photocatalyst.

The irradiation was provided by three halogen lamps (Osram (Berlin, Germany) HALOPAR 30, 75W, 30° aperture angle, luminous flux of 350 lumens) positioned in a vertical support at 40 cm height from the reactor, and they were slightly inclined to direct the focus towards the centre of the beaker containing the catalyst and the CIP solution. The spectral irradiance of the light source is reported in Figure S1. Cooling was provided by adding a constant supply of ice around the reactor with a monitored temperature (35 – 20° C). UV–Visible absorption spectra were recorded using a VARIAN Cary 5000 UV–Vis–NIR spectrophotometer. When working in photo-Fenton mode, a 5×10^{-4} M of H_2O_2 is employed, which is high enough to ensure a large excess (ca. 20 times with respect to the 2.59×10^{-5} M CIP) and low enough for the absorbance of H_2O_2 not to interfere with the spectrophotometric determination of CIP.

3. Results and Discussion

3.1. g-C₃N₄ Characterisation

Synthesized g-C₃N₄ powder and melamine precursor were characterized in terms of structure and morphology (Supplementary Materials, Figures S2–S7). A UV–Vis spectrum was acquired to characterize the melamine precursor before synthesis to g-C₃N₄, and the spectrum shows significant absorbance only in the UV region (<275 nm), as seen in Figure S2. After the melamine synthesis, a powder-like morphology with agglomerated particles under 100 nm in size was observed in the SEM analysis, and the presence of only C and N elements was confirmed from corresponding EDXS spectra (Figure S3). In the FTIR (Figure S4), the peaks that appear in the 1200 – 1700 cm^{-1} region are related to the stretching modes of C=N and C–N hetero-cycles, and the peaks at 875 and 804 cm^{-1} indicate the presence of the stretching mode of the triazine ring [51]. Micro-Raman analysis proves the presence of g-C₃N₄ from the peaks at 211 , 359 , 471 , 588 , 706 , 768 , 984 , 1117 , 1151 , 1232 , and 1312 cm^{-1} , respectively (Figure S5 and Table S1). Also, the peaks 1360 cm^{-1} (D band) and 1580 cm^{-1} (G band) confirm the formation of C–N [52,53]. XRD analysis further confirmed

the presence of the graphitic-like phase of C_3N_4 lattice system given by the (002) peak (Figure S6). An increase in UV absorbance was observed in the 400–500 nm range with a maximum at 400 nm, and the Tauc plot demonstrates that the direct bandgap of the synthesized $g-C_3N_4$ powder is 2.92 eV (Figure S7).

3.2. $FeOx/g-C_3N_4$ Composite Characterisation

Figure 2 presents the FTIR spectra comparison between the $FeOx$ iron urchins film only, $(FeOx/g-C_3N_4)_{in}$ and $(FeOx/g-C_3N_4)_{ex}$ composites. Both the composite materials present the C-N and C=N vibration states in the wavenumbers range between 1200 and 1700 cm^{-1} . A triazine peak is also observed at 804 cm^{-1} . Sharper peak formation in the mentioned range is more evident in the $(FeOx/g-C_3N_4)_{ex}$ composite in comparison to $(FeOx/g-C_3N_4)_{in}$. This can possibly be attributed to the higher mass of $g-C_3N_4$ on top of the $FeOx$ supporting material. The corresponding $FeOx$ spectrum involves the unresolved peaks below 1000 cm^{-1} , which are related to Fe-O stretching vibrations [54]. In Figure 2, a cluster of weak bands found at around 1500 cm^{-1} correspond to the vibration modes of carbonates resulting from interaction of the surface with CO_2 from the air. This is commonly observed in iron oxide surfaces exposed to air humidity, which leads to the formation of hydroxides that are, in turn, susceptible to carbonate formation [55].

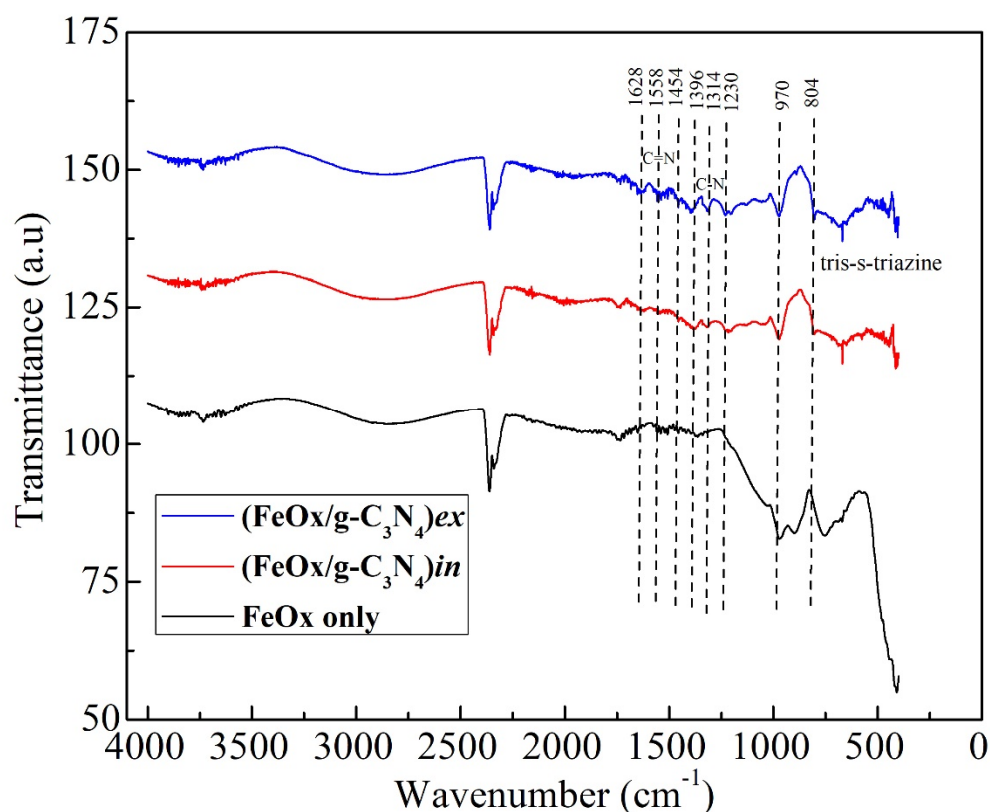


Figure 2. FTIR spectra comparisons between $FeOx$ and the composites $FeOx/g-C_3N_4$.

Micro-Raman analysis was also employed to investigate the properties of the $(FeOx/g-C_3N_4)_{in}$ and $(FeOx/g-C_3N_4)_{ex}$ as well as the reference $FeOx$ support material. The Raman spectra (Figure 3) show the peaks of $g-C_3N_4$ identified at 211, 359, 471, 588, 706, 768, 984, 1117, 1151, 1232, and 1312 cm^{-1} , respectively. For the $(FeOx/g-C_3N_4)_{ex}$, spectrum shows essentially the $g-C_3N_4$ bulk nature due to the complete coverage of the $FeOx$ thin film. The $(FeOx/g-C_3N_4)_{in}$ spectrum presents the $g-C_3N_4$ with the characteristic peaks shifted with respect to the bulk powder $g-C_3N_4$, such as the 521, 749, 810, 999, 1156, 1266, and 1346 cm^{-1} and small traces of $FeOx$ at 298 and 1386 cm^{-1} being the other peaks in

overlap with g-C₃N₄. The shifting on the FeO_x/g-C₃N₄ (in situ) sample is attributed to the atomic lattice compressive stress because of synthesis procedure. In particular, in situ synthesis induces stress modifications on the FeO_x because of the melamine thermal conversion to C₃N₄ on its surface that indeed favours strong adhesion with the substrate. On the other hand, in the ex situ preparation condition, the interaction between the already prepared g-C₃N₄ powder and the FeO_x surface is milder, as proved by the poor adhesion [56]. Peaks assignments are presented in Supplementary Table S1.

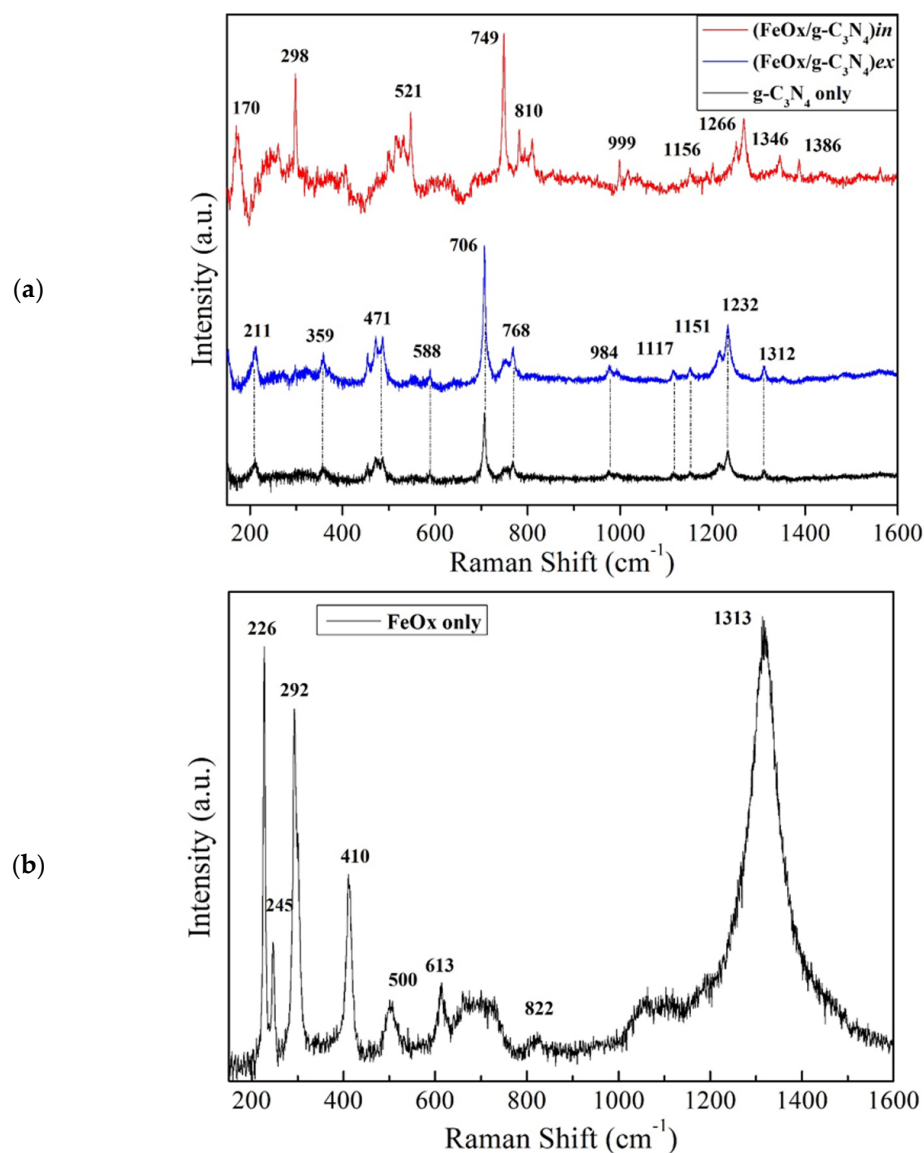


Figure 3. Raman spectra of g-C₃N₄ compared to composites (FeO_x/g-C₃N₄)*in* and (FeO_x/g-C₃N₄)*ex* (a) and FeO_x supporting material (b).

Figure 4 presents the GIXRD patterns for both (FeO_x/g-C₃N₄)*in* and (FeO_x/g-C₃N₄)*ex*. (FeO_x/g-C₃N₄)*ex* clearly presents the peaks at 13.1° and 27.5° corresponding to the (100) and (002) crystal planes of the g-C₃N₄ (JCPDS No. 87-1526). The diffraction peaks typical of hematite are labelled (012), (104), (113), (024), (116), and (122) (JCPDS No. 33-0664), and the observed traces of magnetite phase are labelled (111), (220), (311), (222), and (400) (JCPDS No. 19-0629). According to the growth mechanism of the urchins during the oxidizing annealing, the most oxidized iron phase (Fe₂O₃) is expected to most likely be present on the surface of the nanostructured film, in contact with the solution and with the g-C₃N₄.

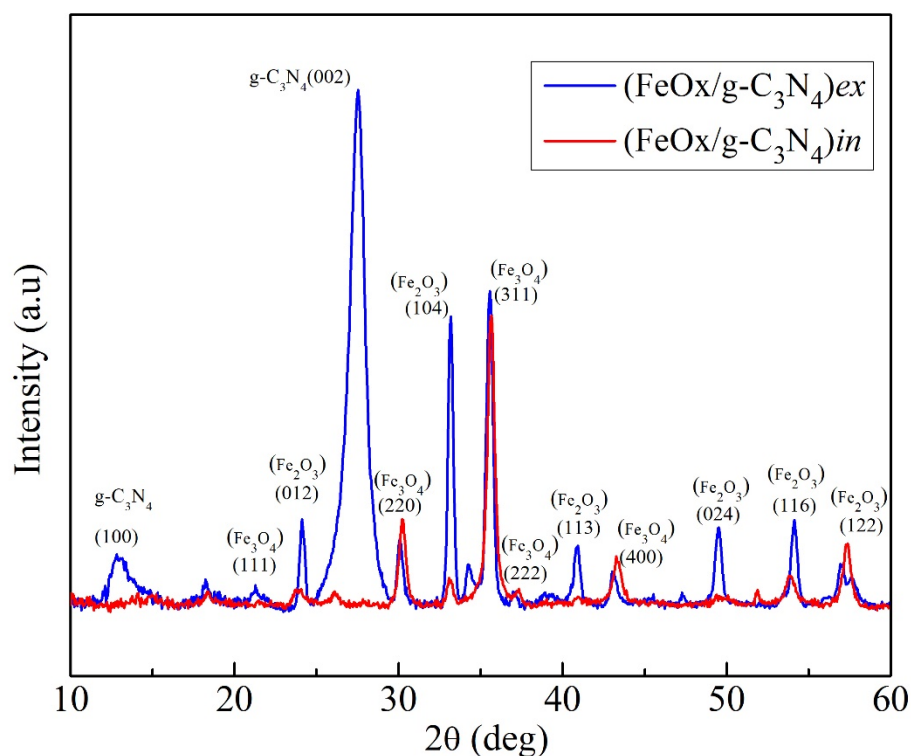


Figure 4. GIXRD patterns for the films $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{in}$ and $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{ex}$ recorded at incidence angle = 0.5 deg.

On the other hand, in the $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{in}$ there is clear evidence of hematite and traces of magnetite. However, in comparison to $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{ex}$, the (002) peak of $\text{g-C}_3\text{N}_4$ is observed slightly shifted toward lower diffraction angle with considerably reduced intensity and also the (100) peak is apparently suppressed. This suggests the intercalation of the layered structure of $\text{g-C}_3\text{N}_4$ by the abundant urchin-like structures (size ~10–20 nm) present on the surface of FeOx contributing to diminish the peak [57,58]. According to the Bragg equation ($\lambda = 2d\sin\theta$), the expanded interlayer distance of the d-spacing due to the intercalation of iron urchins into $\text{g-C}_3\text{N}_4$ layers may lead to the shift of the diffraction peak toward low angle. Moreover, the reduced intensity of the peak shows the possibility of less dense lamellar structure of the $\text{g-C}_3\text{N}_4$ in the composite due to the presence of small amounts of $\text{g-C}_3\text{N}_4$ (in the form of thin petals) on the FeOx surface [59,60]. These structural changes likely imply that in the in situ method of the formation of composite films, the $\text{g-C}_3\text{N}_4$ interacts and reconfigures the surface of FeOx differently than ex situ method.

The absorption spectra and Tauc plot of the $\text{FeOx}/\text{g-C}_3\text{N}_4$ composites are presented in Figure 5. An absorption region can be observed from the visible range (<600 nm) while a constant increase up to the UV range of the spectrum is detected for both composite materials. Interestingly, the $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{in}$ composite film shows lower bandgap (~1.87 eV) than the $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{ex}$ composite (~1.95 eV). Also, the observed bandgaps (1.87 and 1.95 eV) are in agreement with the literature [61]. For both synthesis methods, due to the presence of FeOx as the supporting material, the absorbance is shifted towards the visible part of the spectrum in comparison to the bulk $\text{g-C}_3\text{N}_4$ presented in Figure S7.

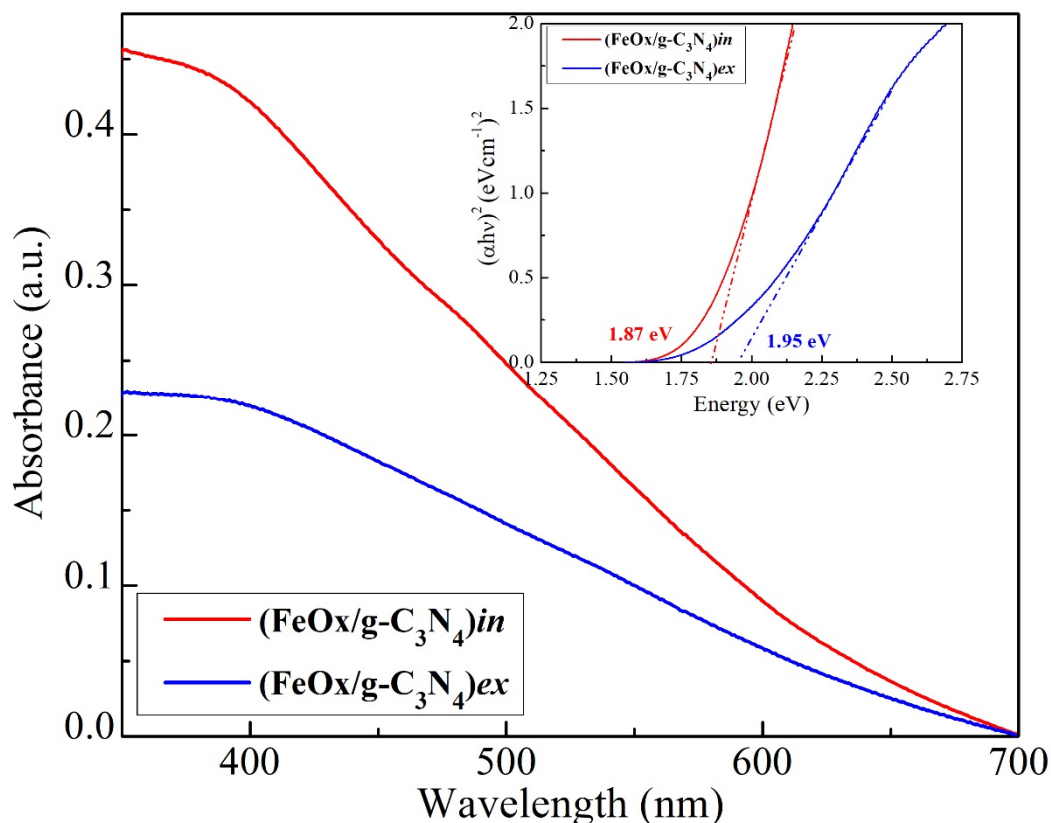


Figure 5. UV–Vis absorption spectra and corresponding Tauc plot (inset) of the synthesized $(\text{FeOx/g-C}_3\text{N}_4)_{in}$ and $(\text{FeOx/g-C}_3\text{N}_4)_{ex}$ composite materials.

Morphology and composition of the synthesized FeOx iron urchins and of the composites $(\text{FeOx/g-C}_3\text{N}_4)_{in}$ and $(\text{FeOx/g-C}_3\text{N}_4)_{ex}$ FeOx were investigated using SEM and EDXS techniques. Figure 6 presents the images of the surface of the FeOx urchin-like structure produced by PLD and annealed at 550 °C for 4 h in a tubular furnace used as the support material. EDXS results essentially confirm the presence of Fe and O on the microstructures (Figure S8). This agrees with previously published reports on this material [40,42]. The mass of the FeOx films was 21 ± 2 mg before the composite preparation steps.

SEM images in Figure 7 show the morphology of the $(\text{FeOx/g-C}_3\text{N}_4)_{in}$ composite. The formation of a petal-like microstructure (Figure 7a,b) is now observed as compared to the bare FeOx urchin. From Figure 7c, it is also observable that urchins present on the FeOx surface possibly intercalate the petal structure. A special formation of petal-like morphology growth is highlighted in (Figure 7d) as a single petal close-up (magnified image in the inset). Moreover, EDXS (Figure S9) confirms the presence of the C, N, Fe, and O elements in the composite film. The mass of the composite is about 10 mg more than the 21 ± 2 mg of the initial FeOx. This corresponds to 5–10% conversion yield of melamine.

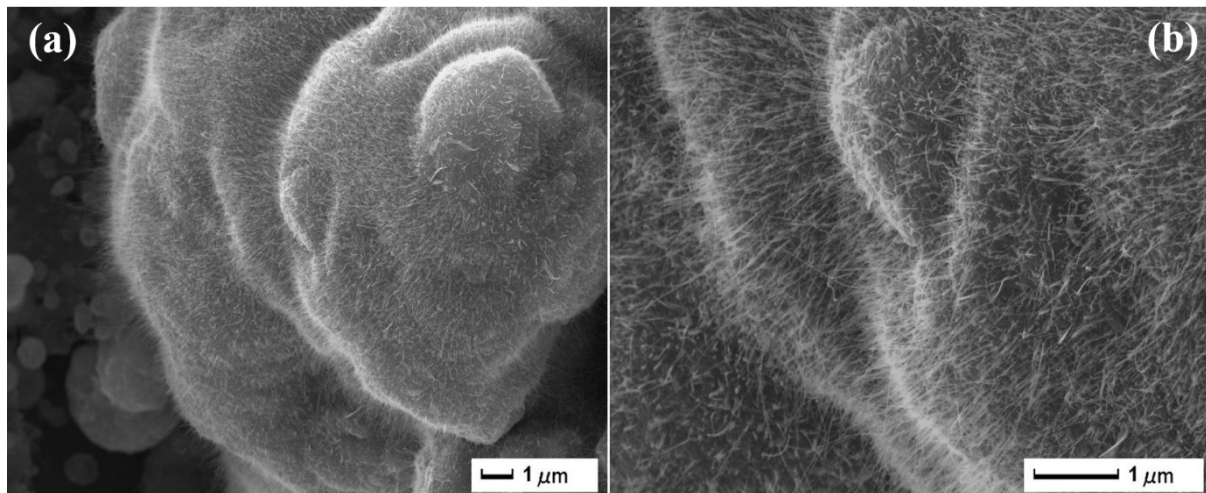


Figure 6. SEM images (a,b) showing the bare surface of the FeOx urchin-like structures employed in the composite with g-C₃N₄.

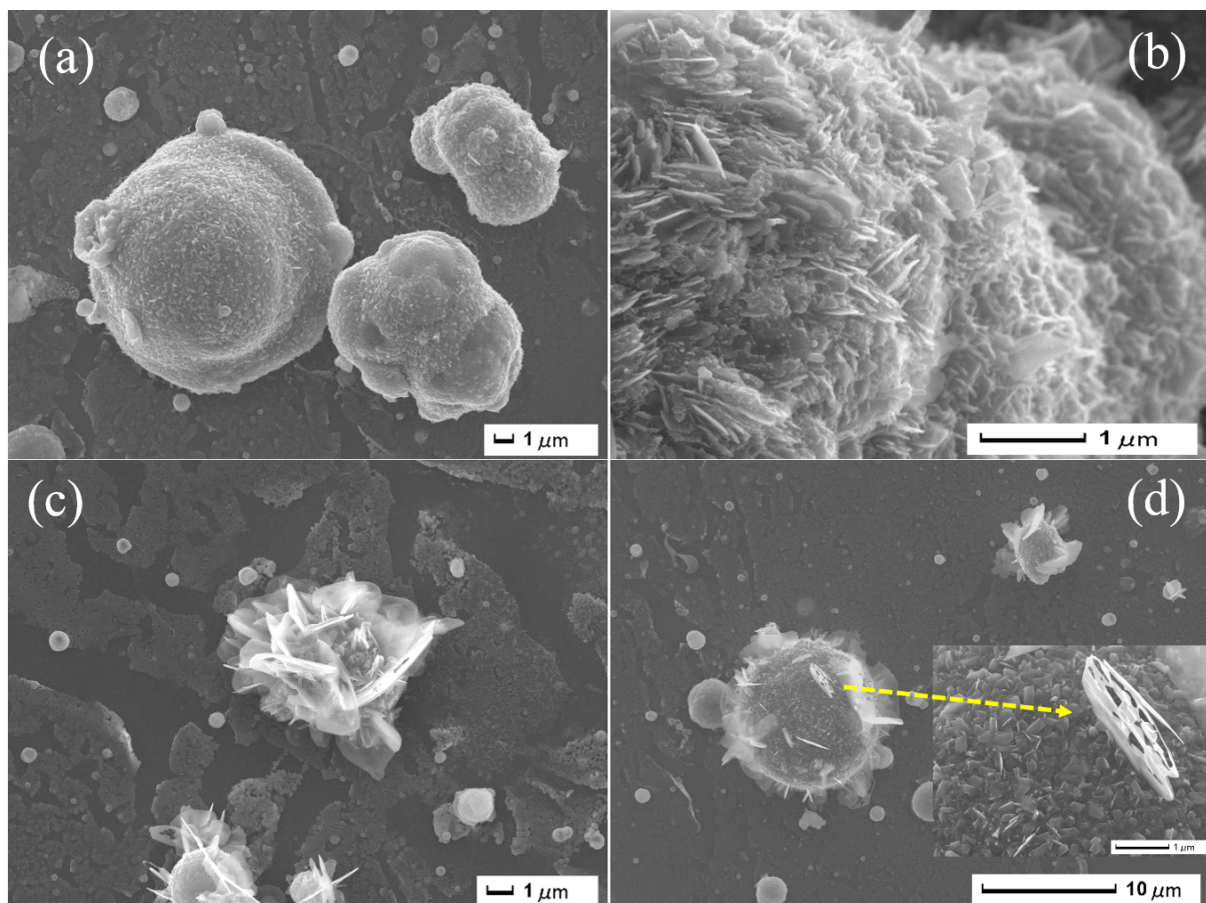


Figure 7. SEM images (a–d) of (FeOx/g-C₃N₄)*in* composite thin films.

Morphology of the synthesized composite (FeOx/g-C₃N₄)*ex* are presented in Figure 8a–c. The visual inspection of the images demonstrates the absence of petal-like morphology and island separation (Figure 8d) between the FeOx particles and g-C₃N₄ deposited on the surface of the iron urchins. In this case, the mass increase was about 40 mg (about 60 mg total composite mass), due to the drying of 1mL solution after the spin-coating process. EDXS (Figure S10) confirms the distinct separation of particles in the composite materials.

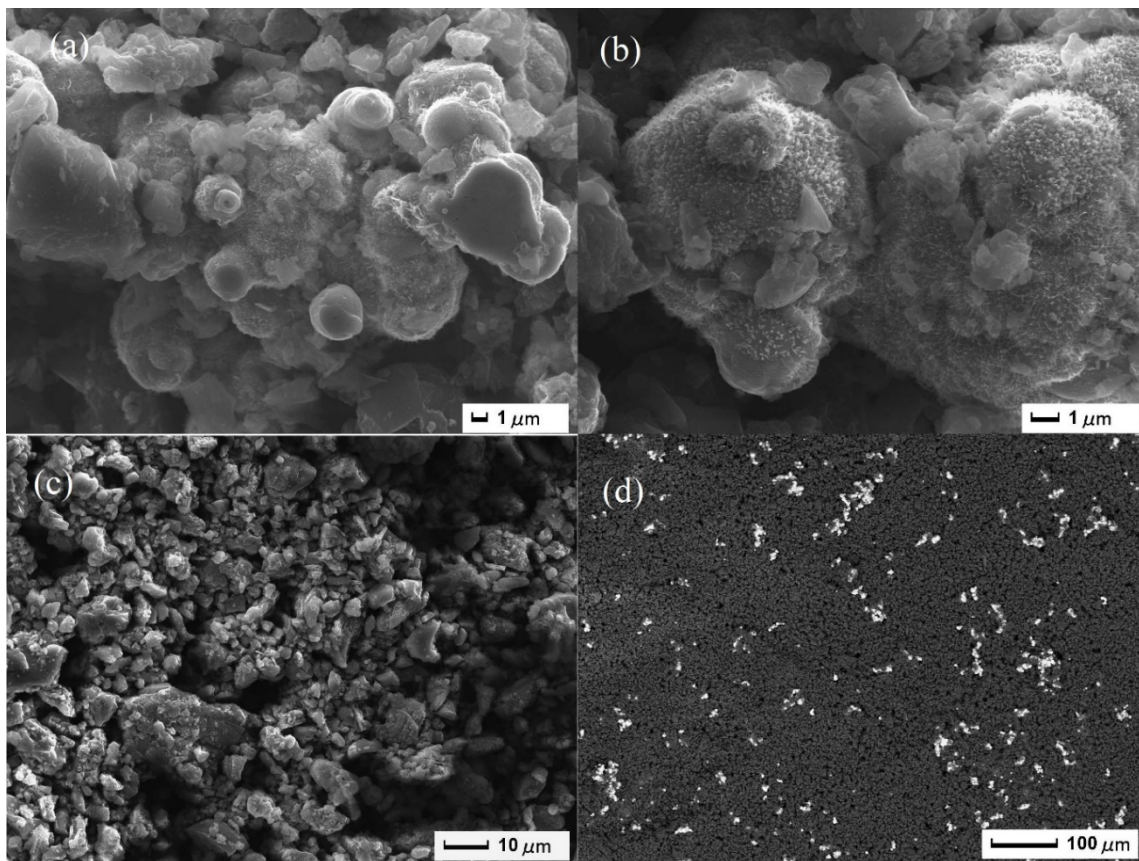


Figure 8. SEM images (a–d) of $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{\text{ex}}$ composite thin films.

The morphology, composition, and crystalline structures of the composite $(\text{FeOx}/\text{g-C}_3\text{N}_4)_{\text{in}}$ were also investigated using HRTEM. Figure 9a–c presents the image of a single petal partially covered by $\text{g-C}_3\text{N}_4$ (darker areas). The magnification of figure 9a shows lattice fringes 0.252 and 0.295 nm and the white arrowheads define intervals corresponding to 10 lattice planes. The SAED spectra of clean single crystal return hematite or magnetite spot diffraction patterns (Figure S11), whereas larger area SAED spectra containing crystalline structure and darker regions show the presence of both Fe_2O_3 and Fe_3O_4 as well as the (002) peak of $\text{g-C}_3\text{N}_4$, which supports the XRD results (SAED patterns were identified with the identical XRD JCPDS card database).

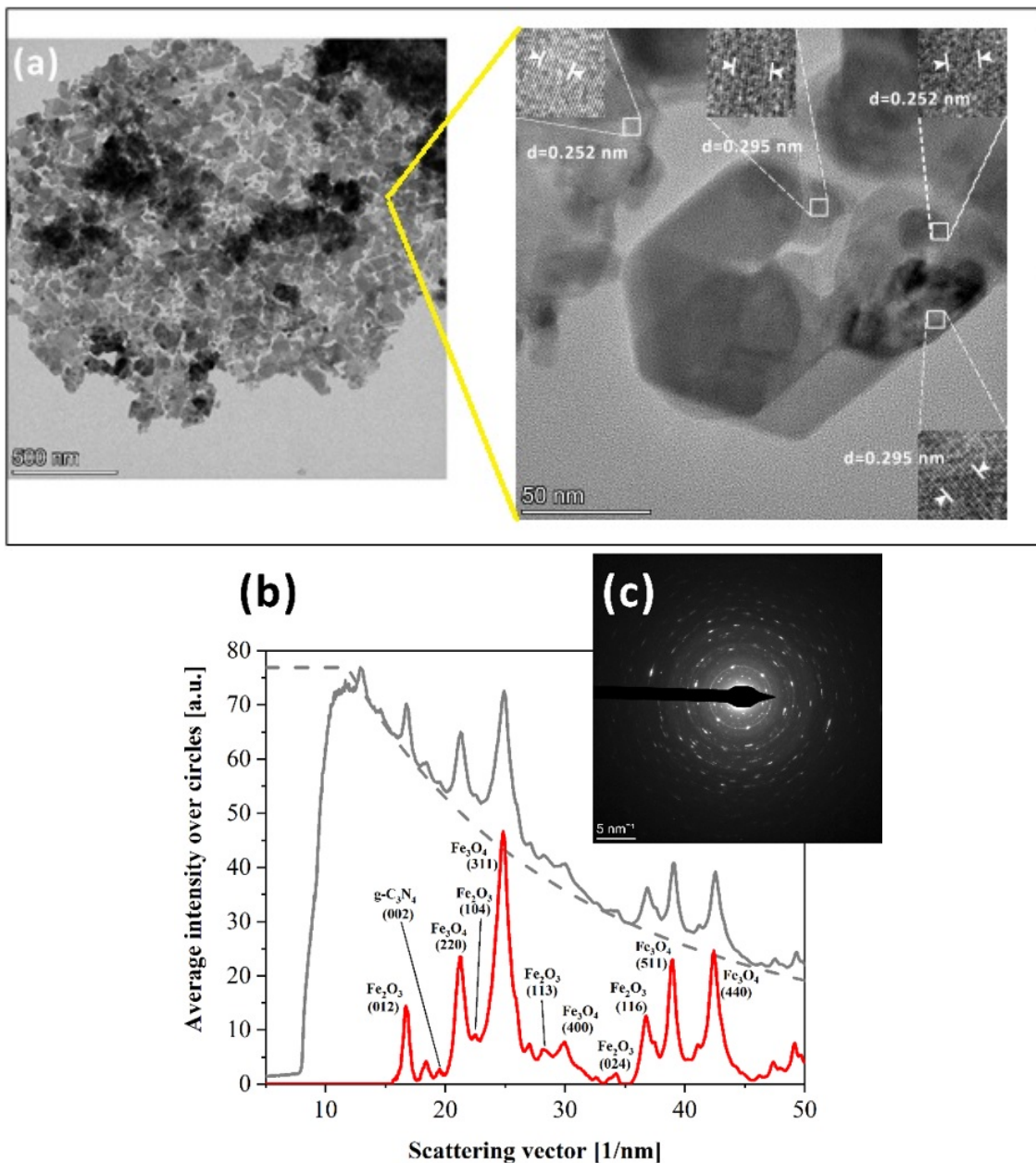


Figure 9. (FeOx/g-C₃N₄)*in* TEM and HRTEM analysis (a). Bright field TEM image of a crystalline petal whose SAED diffraction pattern is given in (c). The intensity profile obtained from (c) is shown in (b): gray lines indicate gross intensity (solid line) and the subtracted background (dashed line), and the red line is the resulting net intensity.

3.3. XPS Analysis

XPS was used to analyse the chemical bonding and composition of all the prepared materials. Figure 10 presents the full survey scan of the FeOx iron urchins, (FeOx/g-C₃N₄)*in*, and (FeOx/g-C₃N₄)*ex* composites that are compared to the FeOx as a support material only. The XPS survey spectra reveals presence of Fe, O, N, and C.

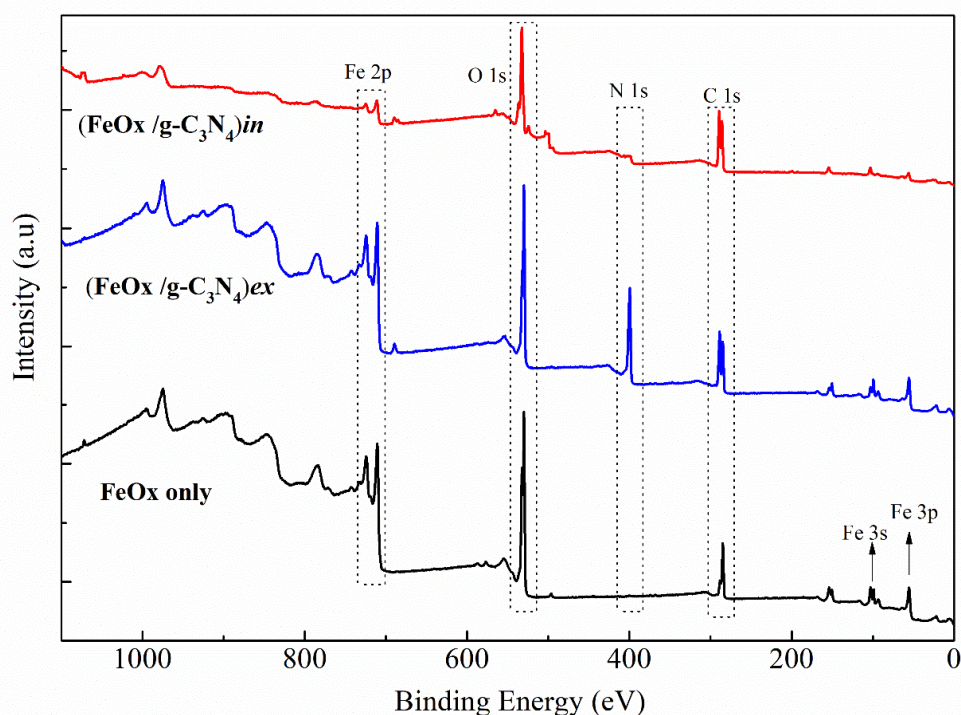


Figure 10. XPS survey scan for all elements in the FeOx urchin and its composites with g-C₃N₄.

Figure 11 shows Fe 2p_{3/2} core level spectra of FeOx and its composites, the Fe 2p survey can be found in the Supplementary Materials (Figure S12a). The Fe 2p_{3/2} core level main peak position (without curve fitting) is located at around 711 eV binding energy (BE) with spin-orbit splitting and a satellite at 719 eV. The peak at 711 eV was further deconvoluted into three peaks, namely 709.8 eV, 710.8 eV, and 712 eV, which correspond to +3 oxidation state of alpha hematite [62–64]. This clearly indicates the presence of dominating alpha Fe₂O₃ phase (hematite) with the +3 oxidation state on the surface of FeOx and (FeOx/g-C₃N₄)*ex* samples. For the XPS spectra of (FeOx/g-C₃N₄)*in*, the main BE positions at 711.5 eV with spin-orbit splitting indicate the presence of a Fe₃O₄ phase. Therefore, the presence of both hematite and Fe₃O₄ cannot be excluded in the samples, thus further supporting our previously reported (Figure 4) XRD results. In Figure 12a, the C1s spectrum of the composite materials contains two peaks at 285 eV and 288.9 eV for (FeOx/g-C₃N₄)*in*, which arise from C–N and sp²-hybridized C in N=C–N. However, for (FeOx/g-C₃N₄)*ex*, the peaks originate at 285.1 eV and 289.3 eV [65,66]. Thus, the C 1s core level spectra of both composite films, i.e., (FeOx/g-C₃N₄)*ex* and (FeOx/g-C₃N₄)*in*, clearly show the presence of the C–N bonding structure coming from g-C₃N₄ with specific contributions as shown in adjacent peaks resulting from the fitted components. A slight modification of peak positions related to g-C₃N₄ was observed in case of the (FeOx/g-C₃N₄)*in* composite film, which could be attributed to interface effects with FeOx [65–70].

The N 1s spectrum (Figure 12b) related to (FeOx/g-C₃N₄)*in* is deconvoluted into three different peaks at 399.8, 401.5, and 402.1 eV, which are attributed, respectively, to sp²-hybridized N in C=N–C, sp³-hybridized N in N–C₃, and C–N–H from amino groups and π excitations in heterocycles. The N 1s core level spectra also clearly indicate the respective bonding contributions (reported with fitted components) originating from the g-C₃N₄ chemical structure. It is also interesting to see that the fitted components with respective chemical structures show modifications in the intensity as well. This is not fully understood yet but probably results from minor changes in the atomic lattice arrangement. Also, the O 1s spectra reported in the Figure S12b, identifies the presence of Fe–O chemical bonding as in Fe oxides with two peaks at 530 eV and 532.6 eV arising from the lattice oxygen in FeOx and the related hydroxide-oxyhydroxide system [71,72]. The small peak

around 532 eV is associated with the presence of adsorbed water on the surface of the samples [73].

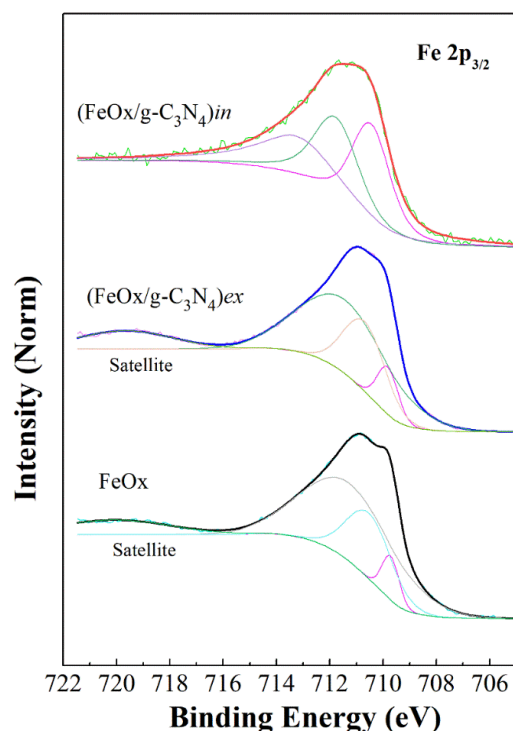


Figure 11. XPS spectra of the Fe 2p_{3/2} core level and deconvolution peaks of the iron urchin and its composites with g-C₃N₄. All the spectra were normalized to the maximum of the peak and curve fitting was achieved using Shirley background and Voigt profiles.

Moreover, looking at the lower bandgap (inset in Figure 5) of the (FeOx/g-C₃N₄)*in* thin film with respect to (FeOx/g-C₃N₄)*ex*, we can suggest that the detected minor differences (1.87 vs. 1.95 eV) could also be related to slight changes in atomic lattice arrangement in the in situ-produced g-C₃N₄ and FeOx likely promoting charge carrier separation and mobility.

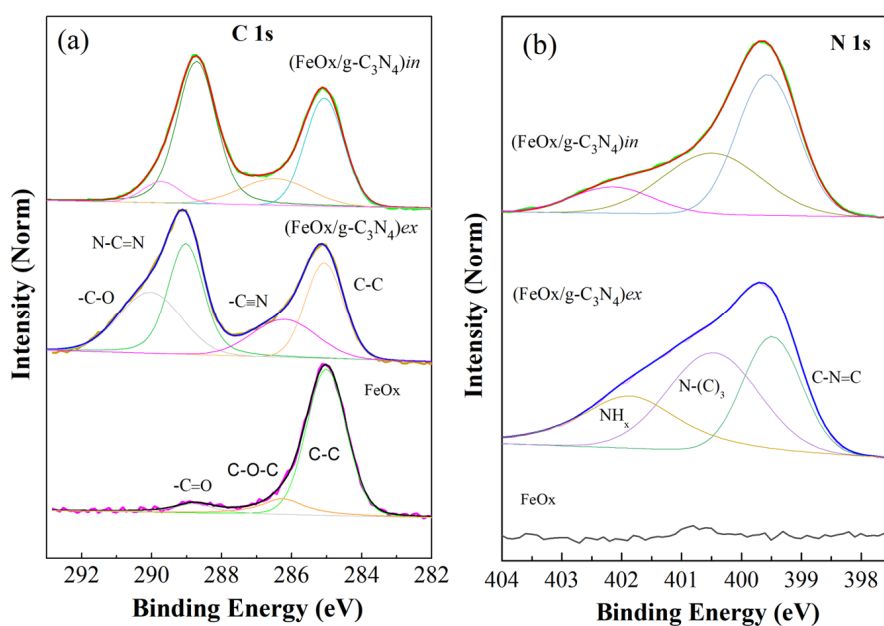


Figure 12. XPS spectra of (a) C 1s and (b) N 1s core levels and the corresponding deconvolution peaks of the iron urchin and its composites with g-C₃N₄. All the spectra were normalized to the maximum of the peak and curve fitting was achieved using Shirley background and Voigt profiles.

3.4. Photocatalytic Activity

The photocatalytic activity of the prepared materials was evaluated at the proof-of-concept level in CIP degradation. First the g-C₃N₄ dispersed powder and coating samples were tested. The adsorption of powders and the poor photocatalytic degradation of CIP in films and powders was observed (Figure S13). Also, the (FeOx/g-C₃N₄)*ex* thin films show only 5% CIP disappearance after 180 min irradiation (Figure S14). The observed inferior CIP removal of (FeOx/g-C₃N₄)*ex* was due to the weak g-C₃N₄ adhesion with consequent partial detachment during the experiment, as pointed out by SEM. Therefore, we have not performed further in-depth analysis of these samples.

The photocatalytic activity of the (FeOx/g-C₃N₄)*in* thin films were compared in the photocatalytic removal of CIP through visible irradiation. Results are reported in Figure 13, and the corresponding UV–Vis spectra obtained are reported in Supplementary Figure S16. Low adsorption (less than 5%) is observed in the dark during the equilibrium period. Upon visible illumination, the system (FeOx/g-C₃N₄)*in* shows a better performance and leads to a 14% of CIP disappearance after 180 min of irradiation with a kinetic constant of $8.28 \times 10^{-4} \text{ min}^{-1}$. The results obtained via (FeOx/g-C₃N₄)*in* are of relevance if one considers the control experiments reported in Figure S15. It is observed that both thermolysis at 50 °C and visible irradiation in the absence of a photocatalyst (photolysis) do not cause any decrease in CIP concentration. This demonstrates that the presence of the composite (FeOx/g-C₃N₄)*in* is mandatory for achieving CIP degradation and that degradation is not a consequence of the temperature increase from the heat developed by the radiation system or photolysis.

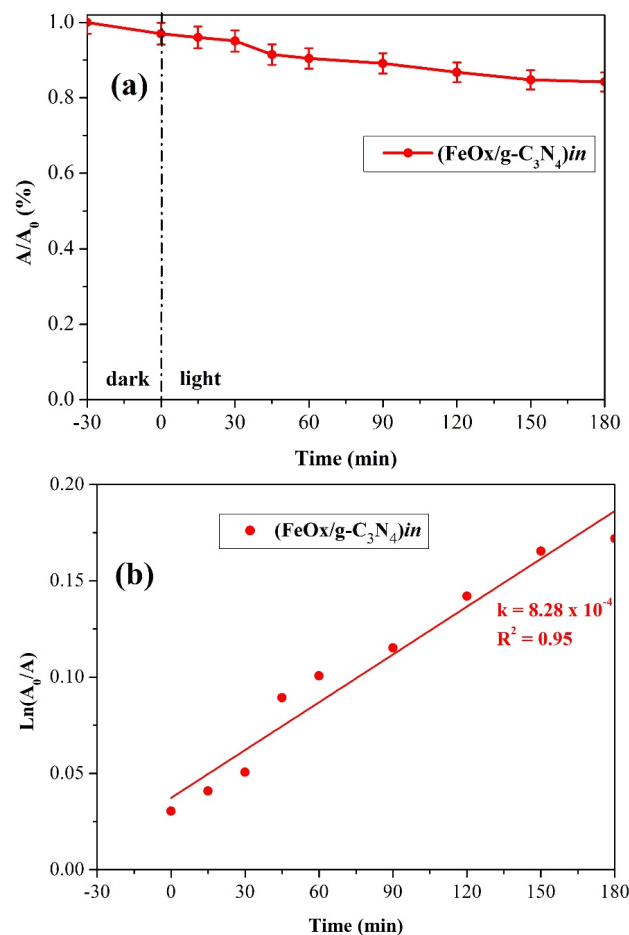


Figure 13. (a) removal yields and (b) corresponding reaction kinetics of the CIP upon irradiation of (FeOx/g-C₃N₄)*in* immersed in aqueous solutions containing CIP (C₀ = 10 ppm).

Given the results obtained from (FeOx/g-C₃N₄)*in*, the photo-Fenton reaction was tested with the addition of H₂O₂. Results are reported in Figure 14, where experiments performed with FeOx alone and in the presence of H₂O₂ 5 × 10⁻⁴ M are reported for comparison. The irradiation of FeOx alone (black) caused a disappearance of CIP of about 15%. When H₂O₂ (5 × 10⁻⁴ M) is present, the material showed a higher CIP disappearance in the dark (17%), possibly due to an initial Fenton reaction, and upon irradiation a disappearance of 35% of CIP is observed with moderate improvements of the degradation after the initial 60 min of illumination on both photo-Fenton cases (FeOx + H₂O₂ and (FeOx/g-C₃N₄)*in* + H₂O₂). This moderate enhancement of degradation is attributed to slight temperature changes and is consistent with the literature [74]. The calculated kinetic constant is $k = 1.6 \times 10^{-3} \text{ min}^{-1}$. A comparison of the results of FeOx (Figure 14) with (FeOx/g-C₃N₄)*in* (Figure 13) shows that their photocatalytic activities are very similar. However, the addition of H₂O₂ (5 × 10⁻⁴ M) to the aqueous solution of CIP in which (FeOx/g-C₃N₄)*in* is present had a booster effect: in fact, 60% of CIP disappearance is achieved after irradiation, a value significantly higher than that observed with FeOx and (5 × 10⁻⁴ M) H₂O₂ alone (6%).

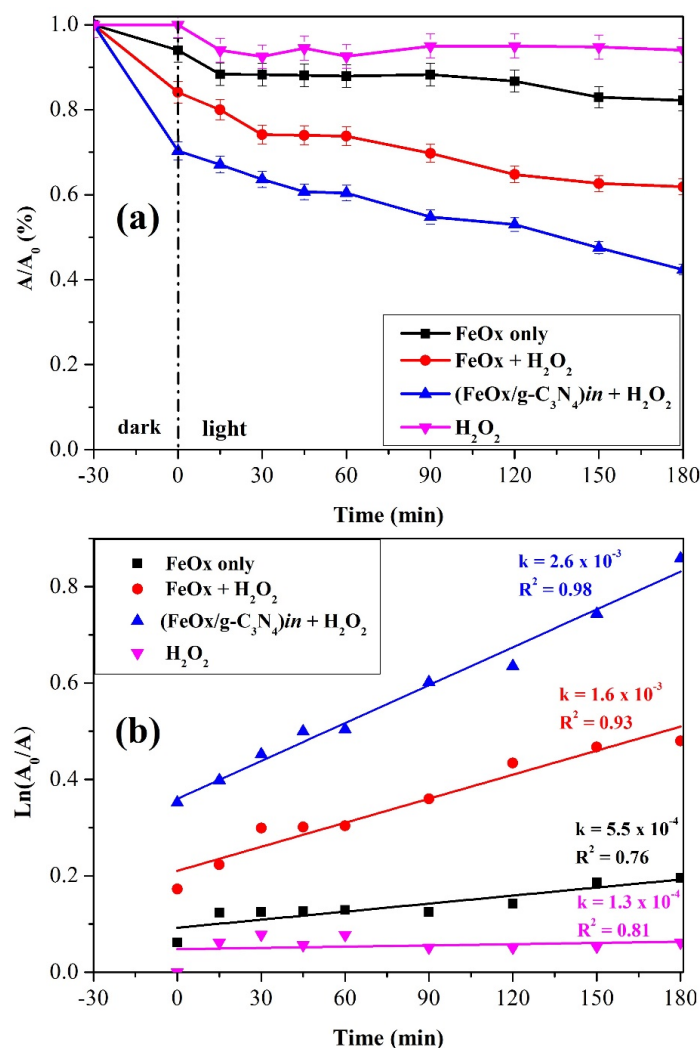


Figure 14. Removal yields (a) and reaction kinetics (b) of the CIP disappearance upon the irradiation of FeOx (black), FeOx + H₂O₂ (5 × 10⁻⁴ M) (red), and FeOx/g-C₃N₄ composites + H₂O₂ (5 × 10⁻⁴ M) (blue). The starting concentration of CIP is 10 ppm.

Therefore, the photo-Fenton process further enhances the degradation efficiency of the (FeOx/g-C₃N₄)*in* composite material compared with the two parts alone. In addition, good adhesion over the glass slides was observed both during photocatalysis and the photo-Fenton reaction.

An overview of the results obtained during the photocatalytic and photo-Fenton experiments are provided in Table 1.

Table 1. Summary of the testing conditions and results for the photocatalysts.

Experimental Condition	Catalyst Form	CIP Adsorption	CIP Removal Yield	Kinetic Constant (k, min ⁻¹)
H ₂ O ₂ (5 × 10 ⁻⁴ M)	No catalyst	0%	6%	1.3 × 10 ⁻⁴
(FeOx/g-C ₃ N ₄) <i>in</i>		5%	13%	8.28 × 10 ⁻⁴
FeOx		5%	15%	5.5 × 10 ⁻⁴
FeOx + H ₂ O ₂ (5 × 10 ⁻⁴ M)		17%	35%	1.6 × 10 ⁻³
(FeOx/g-C ₃ N ₄) <i>in</i> + H ₂ O ₂ (5 × 10 ⁻⁴ M)		30%	60%	2.6 × 10 ⁻³

It has been observed that the (FeOx/g-C₃N₄)*in* composite material exhibits very important photoactivity during CIP removal under photo-Fenton conditions, showing an increase of one order of magnitude of the relative kinetic constant. This activity is higher than that of each counterpart alone. This picture is compatible with the arising of a heterojunction effect, such as a complete (where the solid–liquid interfaces of both materials are redox active) or partial (where only one, i.e., the FeOx conduction band is redox active) Z-scheme in the composite. Another possible explanation for the enhanced performance in the composite is that g-C₃N₄ is simply acting as an electron acceptor, thus temporarily trapping electrons from the FeOx conduction band and inhibiting charge recombination [75]. We consider this last scenario unlikely, as the bandgap of g-C₃N₄ is also compatible with visible absorption.

A likely photocatalysis mechanism for the (FeOx/g-C₃N₄)*in* composite, presented in Figure 15, can be hypothesized based on our data and the current literature. It is known that the degradation of CIP in the presence of iron oxides and g-C₃N₄ occurs mainly through the formation of active species, i.e., superoxide radicals (O₂⁻), hydroxyl radical (·OH), and holes (h⁺) [30,48,76–80]. In the case of (FeOx/g-C₃N₄)*in*, the degradation of CIP is then expected to proceed via two different pathways depending on whether H₂O₂ is present or not. Without H₂O₂ (Figure 15a), the CIP degradation probably proceeds through the formation of a Z-scheme between FeOx and g-C₃N₄ where primarily the (O₂⁻) and (·OH) active species are produced. Note that in this case, ·OH can only be produced through the reaction between h⁺ and water [78–82] and that the superoxide radicals are not very efficient in reacting with CIP [76,83]. When H₂O₂ is added, ·OH can also be produced through the reactions between CB electrons and H₂O₂ and between superoxide and H₂O₂, (Figure 15b) [76,83–87], resulting in a greater availability of highly active ·OH, which would explain the higher activity in the photo-Fenton mode. A detailed investigation of the composite materials working mechanism via transient UV–visible spectroscopy and using selective radical inhibitors will be undertaken in future investigations to confirm this mechanism hypothesis. Nevertheless, we consider the results reported here as a proof-of-concept that the in situ approach is a viable route for achieving heterojunction effects on thin-film photocatalysts for application in pollutant degradation. This is proven by data in Table 2 where a comparison is reported between the best results we obtained with the (FeOx/g-C₃N₄)*in* +H₂O₂ (5 × 10⁻⁴ M) samples and literature data (90–97) for the removal of ciprofloxacin in water and additional information can also be found from literature [88–91].

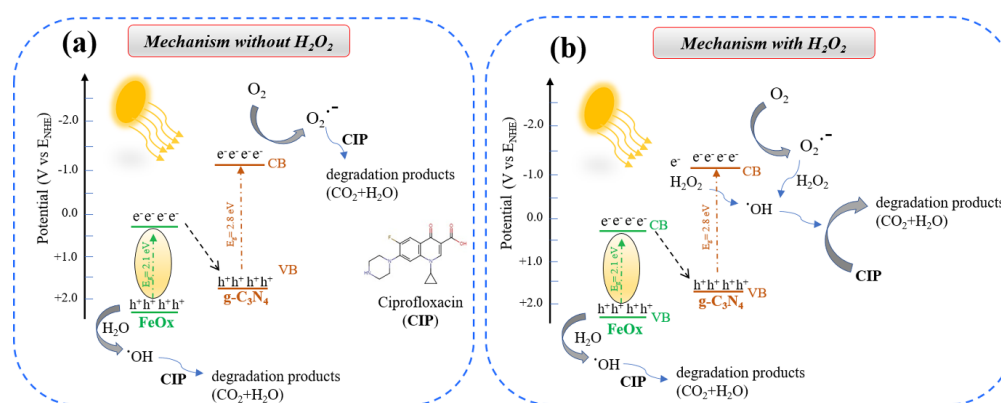


Figure 15. Schematic showing the (FeOx/g-C₃N₄)*in* photocatalyst degradation mechanism (a) without H₂O₂ and (b) with H₂O₂.

Table 2. Comparison for CIP removal with photocatalysts.

Ref	Catalyst	CIP Concentration (ppm)	Tested Volume (mL)	Experimental Time (min)	Illumination Source	Removal Yield
[92]	N,S-CQDs/Bi ₂ MoO ₆ @TiO ₂	20	15	270	Visible light ca. 200 mW/cm ²	90%
[93]	FTO/BaTiO ₃ /SnO ₂	5	75	180	100 W Xe lamp + Ultrasound 24 KHz	60%
[94]	Bi ₂ MoO ₆ @Bi ₂ MoO _{6-x}	20	100	150	6.2 W LEDs between 400 and 700 nm	95%
[95]	TiO ₂ MOCVD	20	100	480	UV LED 365 nm	100%
[96]	(nc-TiO ₂) from Degussa P25	10	100	600	UV lamp 276 nm	100%
[97]	TiO ₂ films grown electrochemically	40	190	180	UV lamp (100–280 nm)	70%
[98]	Ag ₂ MoO ₄	20	100	40	UV lamp (200–400 nm)	90%
[99]	CeO ₂ /CuO/ZnO/Zn	10	100	120	Mercury lamp 120 W – UV light	70%
This work	(FeOx/g-C ₃ N ₄) <i>in</i> + H ₂ O ₂ (5 × 10 ⁻⁴ M)	10	50	180	Visible Halogen lamps, 225W	60%

4. Conclusions

The development of composites produced by combining iron oxide urchins (FeOx) with g-C₃N₄ following two different procedures (FeOx/g-C₃N₄)*in* and (FeOx/g-C₃N₄)*ex* was reported along with its application in the photocatalytic degradation of ciprofloxacin pharmaceuticals.

The PLD procedure to obtain annealed hematite iron urchins followed by the drop-casting of the melamine precursor to thermally condense the g-C₃N₄ (FeOx/g-C₃N₄)*in* composite thin film evolved into to a petal-like morphology with a high surface area featuring good absorption in the visible range (<600 nm). This composite material exhibits an improved photocatalytic performance when compared to the single components, with the optimal condition for ciprofloxacin degradation (from 20 to nearly 60%) observed under the photo-Fenton condition. These results are compatible with a heterojunction effect in the composite, likely of the Z-scheme type. The advantages with (FeOx/g-C₃N₄)*in* rely on the mechanical stability of the coating on the glass surface, which allows us to overcome the problems related to the use of nanoparticles in suspension. The research presented in this paper will be further developed as we consider the reported results as a significant

starting point for obtaining a Z-scheme strategy specifically for thin-films. Indeed, further activities aimed at elucidating the working mechanism of these composites under light are ongoing.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app131910591/s1>, Section S1: Different aspects regarding ex situ and in situ materials synthesis methods, Section S2: light source for photocatalysis experiments, Section S3: characterisation of g-C₃N₄ bulk and Section S4: FeOx composite films, Section S6: Raman peak assignments, Section S5: supporting information for photocatalytic tests, and Section S7: UV-Vis spectra from the photocatalysis experiments. Figure S1: Measured and normalized spectrum of visible light lamps (75 W each) employed in this work (Osram HALOPAR 30, 75 W, 30° aperture angle, luminous flux of 350 lumens); Figure S2: Absorption spectrum of melamine used as precursor to g-C₃N₄ synthesis; Figure S3: SEM image of g-C₃N₄ powder synthesized at 550 °C 4h and its corresponding EDXS spectra; Figure S4: FTIR spectra of the melamine and g-C₃N₄ synthesized at 550 °C 4 h; Figure S5: Raman spectra of melamine and g-C₃N₄ synthesized at 550 °C 4h; Figure S6: GIXRD pattern of the synthesized g-C₃N₄ powder at 550 °C; Figure S7: UV-Vis absorption spectra and Tauc plot of the g-C₃N₄ synthesized at 550 °C 4h; Figure S8: EDXS spectrum of the surface of the FeOx urchin like structures used as support in the composite with g-C₃N₄; Figure S9: EDXS spectra from 4 different regions of the (FeOx/g-C₃N₄)_{in} composite thin films; Figure S10: EDXS spectra from two different regions of the (FeOx/g-C₃N₄)_{ex} composite thin films; Fig. S11 (FeOx/g-C₃N₄)_{in} TEM image and corresponding larger area SAED pattern; Figure S12 XPS spectra of (a) Fe 2p (top left) and specifically Fe 2p_{3/2} (top right) and (b) O1s core levels without curve fitting of the iron urchin and its composites with g-C₃N₄; Figure S13: Removal yields of the CIP disappearance upon irradiation of g-C₃N₄ 4h in powder (black) and in the film (blue) in aqueous solutions containing CIP (C₀ = 10 ppm); Figure S14: Removal yields of the CIP disappearance upon irradiation of (FeOx/g-C₃N₄)_{ex} thin films immersed in aqueous solutions containing CIP (C₀ = 10 ppm); Figure S15: Control experiments: aerated aqueous solution of CIP (10 ppm) maintained at 50°C in the dark (red) or visible irradiated (blue) in the absence of any photocatalyst; Table S1: modes of every peak identified in the Raman measurements. The peaks identifications are based on the literature [100–103]; Figure S16: UV-Vis spectra from obtained from the photocatalysis and photo-Fenton experiments.

Author Contributions: Conceptualisation: M.F., O.P.B. and M.O.; sample preparation and analysis: M.F., O.P.B., R.E., A.M. (Alessandra Molinari), P.R. and C.M.; original draft preparation: M.F. and O.P.B.; writing—Review and editing: M.O., A.M. (Antonio Miotello), A.M. (Alessandra Molinari), R.E. and C.M.; supervision: M.O. and A.M. (Antonio Miotello); funding acquisition: A.M. (Antonio Miotello) and M.O. All authors have read and agreed to the published version of the manuscript.

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