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Three-dimensional graphene encapsulated Ag–ZnFe₂O₄ flower-like nanocomposites with enhanced photocatalytic degradation of enrofloxacin†

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Three-dimensional (3D) Ag–ZnFe₂O₄-reduced graphene oxide (rGO) was successfully synthesized using a hydrothermal and photo-reduction method, and the morphological differences of the materials were observed. Their photocatalytic activity was evaluated by photocatalytic degradation of enrofloxacin (ENR) under visible-light irradiation. The results indicated that Ag–ZnFe₂O₄-rGO exhibited superior photocatalytic properties and good stability. In this research, the enhancement of photocatalytic performance is mainly attributed to the electron channelization ability of rGO, which traps the photoexcited electrons of ZnFe₂O₄ on its π framework, and reduces the electron–hole recombination rate. Moreover, the high surface area of 3D pompon mum flower-like ZnFe₂O₄ provides more reactive sites. In addition, free radical capture and ESR experiments as well as pathway analysis of degradation also confirmed that superoxide radicals ($\cdot\text{O}_2^-$) and photo-generated holes from Ag–ZnFe₂O₄-rGO were the main active species in the degradation progress of ENR.

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1. Introduction

Different environmental pollution includes soil, air, water, heat, noise and light pollutions, and water pollution is among the main environmental challenge confronted by society. Nowadays, with society and information technology developing, the degradation of organic contaminants has been investigated using various techniques and systems. There is no doubt that organic contaminants will, directly or indirectly, have a great influence on our academic studies.^{1–4} Enrofloxacin (ENR), as a representative of fluoroquinolones, is widely used to treat various infections in animals. Traditional sewage treatment cannot effectively eliminate excess antibiotics, so that ENR is often detected in various water environments.⁵ Consequently, it is imperative for us to develop a highly efficient steady strategy to degrade subaqueous ENR. As is known to us all, photocatalytic materials can effectively convert solar energy into

chemical energy to degrade water and air contaminants, which is of great significance for addressing environmental pollution issues in modern society. Given the serious energy crisis, semiconductor photocatalysis can be a promising technology for the complete elimination of various contaminants.⁶ In the frontier area of catalysis, it is currently a hot topic that plasmonic photocatalysts characterized by distinct surface plasmon resonance (SPR) absorptions over a wide range of visible-light regions are promising materials as high-performance visible-light-energized photocatalysts. Until now, spinel ZnFe₂O₄ has drawn broad attention due to its narrow band gap of approximately 1.9 eV, which can be excited by visible-light and ability to utilize sunlight. In addition, ZnFe₂O₄ works as a photocatalyst that has been widely evaluated in remediation of polluted environmental because of its excellent photoelectricity transformation ability and photosensitive effect. However, the low separation rate and high recombination rate of photo-generated electrons (e^-) and holes (h^+) can largely obstruct applications.^{7,8} Therefore, some co-catalysts are introduced into the photocatalytic system to improve the separation efficiency of photo-generated e^-/h^+ pairs. The photocatalytic activity of the catalyst was improved by reducing the photo-generated e^-/h^+ pair recombination rate.⁹ Carbon materials such as graphene and carbon nanotubes have been used as co-catalyst materials.^{10,11} Ag nanoparticles (Ag NPs), as facile and efficient light absorbers, were often modified on the surface of ZnFe₂O₄, which exhibit enhanced photocatalytic performance against

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bacterial infection. Nevertheless, the high cytotoxicity of Ag^+ released from Ag NPs severely limited the application of hybrid $\text{ZnFe}_2\text{O}_4/\text{Ag}$ NPs based antibacterial materials in the biomedical field.^{12,13}

Graphene oxide (GO), a honeycomb and one-atom-thick structured carbon material, whose basal plane and edge are decorated with abundant oxygen-containing functional groups (e.g., $-\text{OH}$, $-\text{COOH}$, $\text{C}=\text{O}$, $-\text{CH}(\text{O})\text{CH}^-$), has been verified to be an excellent catalyst carrier and promoter.¹⁴ Due to its unique structure and excellent electronic, electrochemical, optical, thermal and mechanical properties, GO has already been possessed broad application prospects. Simultaneously, GO has a large specific surface area, a high electron transfer efficiency, and excellent adsorption.¹⁵ Taking the above highlighted advantageous features into account many metal oxide-GO based nanocomposites were fabricated with increase visible-light absorptivity and longer lifespan of exciton pairs.¹⁶ Generally, sole semiconductor photocatalyst demonstrates poor photocatalytic performance due to the rapid recombination of photogenerated charge carriers and low quantum efficiency. Heterojunction formation is an efficient way to extend the visible light absorption range and accelerate the charge separation.¹⁷ In this regard, a few researchers have studied this area in detail and many semiconductors such as $\text{ZnFe}_2\text{O}_4\text{-Ag/rGO}$,¹⁸ $\text{H-PPAN/rGO-g-PAO@Ag}^+/\text{Ag}$,¹⁹ $\text{rGO-MFe}_2\text{O}_4$ ($\text{M} = \text{Ni}, \text{Co}, \text{and Zn}$),²⁰ $\text{Ag-ZnFe}_2\text{O}_4@\text{rGO}$,²¹ $\text{ZnFe}_2\text{O}_4@\text{graphene}$ ²² and $\text{ZnFe}_2\text{O}_4/\text{RGO/In}_2\text{O}_3$ (ref. 23) have been effectively synthesized. Nanocomposites containing magnetic materials are highly advantageous as they can be easily be separated from the medium. In this regard, Jiang *et al.* synthesized graphene- WO_3 nanocomposites, exhibits the highest catalytic performance and the corresponding removal efficiency can reach 99.1% with 60 min treatment time.²⁴ Wang *et al.* after the introduction of graphene in Au NPs-PtDPAP/CdS, the degradation efficiency on TC was further improved (90% in 3 h).²⁵ In addition, both ZnFe_2O_4 and ZnFe_2O_4 -based composites such as ZnFe_2O_4 -reduced graphene oxide hybrid can act as photo-Fenton-like catalysts to improve the degradation rate of organic antibiotics under visible-light irradiation in the presence of H_2O_2 .²⁶ In recent years, in order to treat wastewaters that contain these kinds of pharmaceuticals which cannot be degraded biologically, Advanced Oxidation Processes (AOPs) gain attention. AOPs which do not require high temperature and pressure, produce reactive radicals ($\cdot\text{OH}$, $\cdot\text{O}_2^-$) at medium conditions. Formed radicals oxidize organic antibiotics to convert them to CO_2 and H_2O . Thus, the photocatalytic oxidation which is the one of AOPs was used in to degrade enrofloxacin (ENR) under visible-light illumination.²⁷ Photocatalytic oxidation (photocatalysis) can be declared as acceleration of a photoreaction by presence of a proper photocatalyst.

In this contribution, a novel 3D separable and recyclable $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ photocatalyst with the pompon mum flower-like and photocatalytic degradation was successfully prepared *via* a facile hydrothermal, and heat treatment, as well photo-reduction method. The graphene oxide (GO) was reduced to the reduced graphene oxides (rGO) and covered on the surface of the ZnFe_2O_4 nanoflowers. Ag NPs were deposited *in situ* on

rGO by photo-reduction Ag^+ to form the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ composites. The synthesized exhibited high photocatalytic activity on the degradation of the ENR under visible-light irradiation. The magnetic properties of ZnFe_2O_4 could make the separation of the nanocomposite easier, avoiding environmental contamination from processing. Moreover, the nanocomposites represented high photocatalytic stability and reusability. The photocatalytic properties of $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ for antibiotic degradation were discussed under visible-light irradiation, and the structure-activity relationship between electronic structure, and photocatalytic activity were also studied. In addition, a reasonable photocatalytic mechanism for the degradation of antibiotics was also explained in detail. Simultaneously, we explored the conversion pathway of ENR in the photocatalytic degradation process.

2. Experimental section

2.1 Synthesis of 3D ZnFe_2O_4 pompon mum nanoflowers

3D ZnFe_2O_4 nanoflowers have been synthesized through a simple hydrothermal method using ZnCl_2 and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ as Zn and Fe sources, respectively. Firstly, in a typical synthesis procedure, $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ (1.08 g, 4.0 mmol), ZnCl_2 (0.27 g, 2.0 mmol) were dissolved in ethylene glycol (40 mL), and then transferred to a Teflon-lined stainless-steel autoclave (50 mL). The autoclave was kept at 180 °C for 30 min under Ar flow. Secondly, the urea (0.60 g, 10.0 mmol) was added into above solution quickly. After continuously mechanical stirring at 200 °C for 2 h, the yellow precursor precipitate (ZnFe -alkoxide precursor) was collected by centrifugation, and washed with absolute ethanol and deionized water, repeatedly. Finally, the precursor was further annealed at 450 °C in N_2 for 3 h with a relatively slow heating rate of 5 °C min^{-1} to obtain 3D ZnFe_2O_4 nanoflowers.

2.2 Synthesis of the $\text{ZnFe}_2\text{O}_4\text{-rGO}$ nanocomposites

In the following step, $\text{ZnFe}_2\text{O}_4\text{-rGO}$ was synthesized as follows: 0.1 g of the as-obtained ZnFe_2O_4 nanoflowers was dispersed into 20 mL of deionized water under vigorous agitation, followed by adding 25 mL of GO solution (1.0 mg mL^{-1}), stirring for 30 min and then adding 10 mL of CTAB (0.5 mg mL^{-1}) solution to produce graphene oxides encapsulated $\text{ZnFe}_2\text{O}_4\text{-rGO}$ composites. Graphene oxides would be reduced to the rGO during the subsequently annealing treatment of the $\text{ZnFe}_2\text{O}_4\text{-GO}$ at 500 °C for 2 h in Ar, and finally 3D graphene encapsulated $\text{ZnFe}_2\text{O}_4\text{-rGO}$ composites could be harvested. It was cooled naturally, solid separated, washed with ethanol and Milli-Q water, repeatedly, dried at 65 °C (for 12 h).

2.3 Synthesis of the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ nanocomposites

Ag NPs were embedded on the as-acquired 3D $\text{ZnFe}_2\text{O}_4\text{-rGO}$ nanoflowers through photo-irradiation reduction by Ag^+ ions. In particular, solid AgNO_3 (10.0 mg) and methanol (2.0 mL) solution were added to the obtained aqueous suspension (0.5 g, 25 mL) of the $\text{ZnFe}_2\text{O}_4\text{-rGO}$ nanocomposite, and 100 W mercury lamp was irradiated at $\lambda = 365 \text{ nm}$ for 5 h. The black solid (Ag-



ZnFe₂O₄-rGO) was separated by an external magnet and washed with Milli-Q water and ethanol, repeatedly, and then dried at 120 °C for 2 h. In the result and discussion section, the inlay situation of Ag NPs is analyzed and discussed in detail. Fig. S1† presents the proposed formation process of the Ag-ZnFe₂O₄-rGO nanocomposites.

2.4 Photocatalytic activity measurement

The photocatalytic degradation activity of the as-acquired Ag-ZnFe₂O₄-rGO photocatalysts was evaluated by the photocatalytic degradation of ENR under visible-light irradiation. First of all, a 300 W Xe lamp with a UV cutoff filter ($\lambda > 400$ nm) was used as the visible-light source ($\lambda = 465$ nm) in the photocatalytic degradation reaction. Briefly, the Ag-ZnFe₂O₄-rGO (15 mg) was dispersed in 50 mL of an aqueous ENR solution (10 mg L⁻¹) in this work. Then, the photocatalyst was fully in contact with ENR molecules to ensure the adsorption-

desorption equilibrium by shaking them for 15 min using a blender in the dark. Moreover, at predetermined time intervals (5 min), 3.0 mL of liquid was drawn from the degradation reaction solution, and the supernatant was extracted by centrifugation (10 000 rpm, 20 min). In addition, the photocatalytic degradation reaction is degraded in the degradation tank at room temperature. Finally, the residual concentrations of ENR in the reaction solution were detected by UV-vis spectrophotometry at $\lambda = 271$.

The photodegradation efficiency (η_{eff}) of the ENR solution was determined according to the following eqn (1):²¹

$$\eta_{\text{eff}} = \left(1 - \frac{C_t}{C_0}\right) \times 100\% = \left(1 - \frac{A_t}{A_0}\right) \times 100\% \quad (1)$$

where A_0 and C_0 are the absorbance and concentration of the pure antibiotic solution (mg L⁻¹), A_t and C_t are the absorbance and the concentration of ENR at a given reaction time (mg L⁻¹).

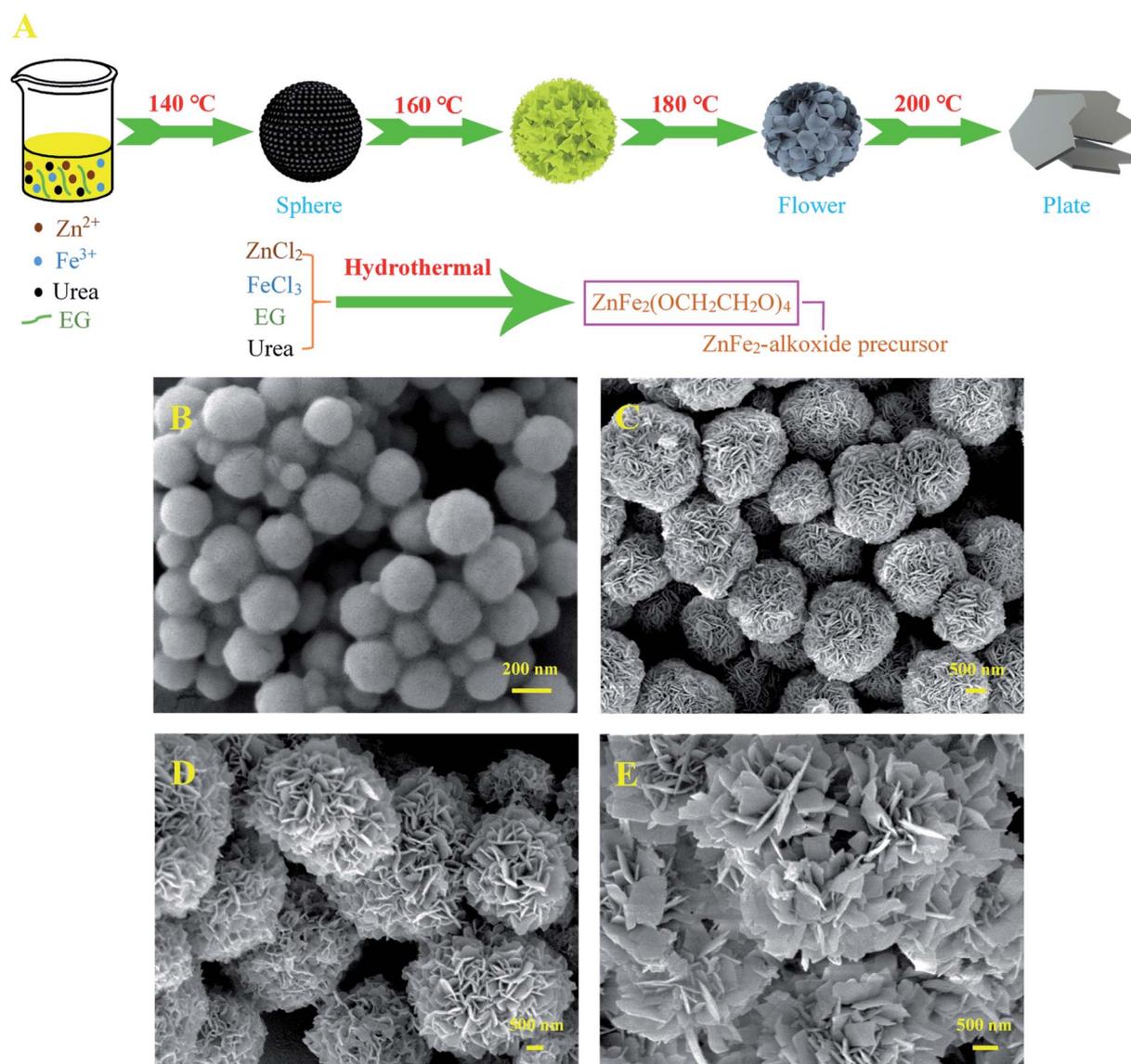


Fig. 1 (A) Schematically illustration for the formation mechanism and (B–E) FE-SEM images of as-obtained ZnFe-alkoxide precursor at various hydrothermal temperature: (B) 140 °C, (C) 160 °C, (D) 180 °C, and (E) 200 °C.



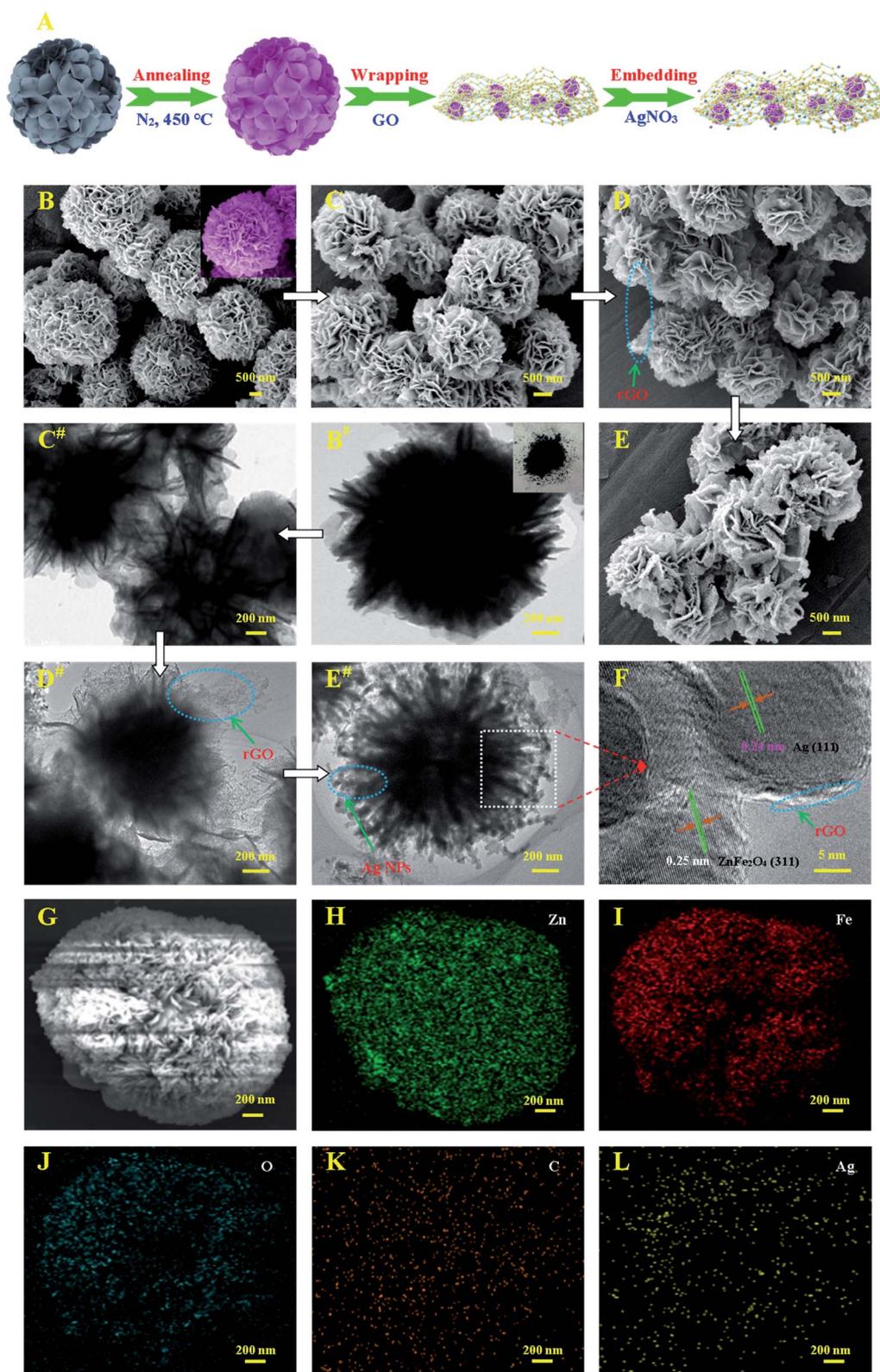


Fig. 2 (A) Schematic illustration of the preparation process for the Ag-ZnFe₂O₄-rGO. The SEM images (B, C, D, and E) and TEM images (B[#], C[#], D[#], and E[#]) of as-prepared ZnFe-alkoxide precursor, ZnFe₂O₄, ZnFe₂O₄-rGO, and Ag-ZnFe₂O₄-rGO. The insets of C and C[#] present the magnified FE-SEM images and as-prepared ZnFe₂O₄. (F) is the high-resolution image of corresponding area in E[#] with further enlarged images of ZnFe₂O₄ and Ag NPs. The Energy dispersive X-ray (EDX) elemental mapping analysis of Zn (H), Fe (I), O (J), C (K) and Ag (L) elements for Ag-ZnFe₂O₄-rGO (G).



The specific photocatalytic degradation process is shown in Fig. S2.†

2.5 Reaction kinetics

Kinetic analysis was studied to evaluate the catalytic performance of Ag-ZnFe₂O₄-rGO more visually. It is universally acknowledged that the reaction of organic chemicals on heterogeneous catalysts can be represented by the Langmuir-Hinshelwood kinetic model. For photocatalytic degradation, ENR must first be adsorbed on the surface of the Ag-ZnFe₂O₄-rGO nanocomposite material and fully contacted, and then react with the reactive species on the photocatalyst for photodegradation. Put it another way, the Langmuir-Hinshelwood kinetic model can be used to depict the photocatalytic degradation of ENR by Ag-ZnFe₂O₄-rGO:²⁸

$$r_0 = \frac{dC_t}{dt} = \left(k_r \frac{K_a C_t}{1 + K_a C_t} \right) \quad (2)$$

where r_0 is the initial rate for ENR photodegradation reaction, C_t is the ENR concentration (mg L⁻¹), k_r is the intrinsic rate constant, K_a is the Langmuir coefficient of ENR, and t is the reaction time (min). When the value of $K_a C_t$ is much less than 1, eqn (2) can be simplified to the pseudo-first-order kinetics:

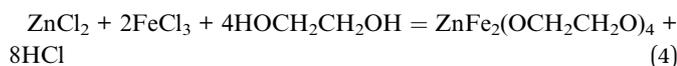
$$\ln \frac{C_t}{C_0} = -k_{\text{pfo}} t \quad (3)$$

where k_{pfo} is the pseudo-first-order reaction rate constant for ENR photodegradation (min⁻¹).

3. Result and discussion

3.1 Structure and morphology characterization of the Ag-ZnFe₂O₄-rGO nanocomposites

In this study, we found that the hydrothermal temperature has an important influence on the morphology of the pre-synthesized ZnFe-alkoxide precursor, which was transferred into ZnFe₂O₄ with conformal morphology finally after a facile thermal treatment in N₂. The possible morphological evolution process to form the ZnFe-alkoxide precursor is schematically depicted in Fig. 1A. The reaction equation can be briefly depicted as follows:



Moreover, the alkaline substance (urea) added in the solution system rapidly decomposed and released a large number of NH₃ (alkaline) to eliminate the adverse effects of H⁺ (HCl) generated in the reaction process (NH₃ + H⁺ = NH₄⁺), thus greatly facilitating the nucleation and growth of ZnFe-alkoxide precursor.²⁹ When the reaction system was maintained at 140 °C for 12 h, only some ZnFe-alkoxide microspheres could be clearly observed (Fig. 1B) with the size of approximately 200 nm in diameter. With the reaction temperature gradually increasing to 160 °C for 12 h, the ZnFe-alkoxide nanospheres became larger, and cracks appeared on the surface to form

sheets (Fig. 1C). Increasing the temperature to 180 °C leads to the continuous growth of these sheet-like subunits, thus forming pompon mum flower-like ZnFe-alkoxide precursor (Fig. 1D). On the contrary, with the continuous increase of the hydrothermal temperature to 200 °C (Fig. 1D), the flower-like structure of ZnFe-alkoxide is severely destroyed by the high temperature and gradually evolved into monodisperse plate-like morphology with irregular edges. Obviously, the hydrothermal temperature performs an important role in controlling the morphology of the finally obtained 3D ZnFe₂O₄ nanoflowers. That is to say, it is crucial to sustain the hydrothermal temperature at about 180 °C to obtain 3D flower-like ZnFe₂O₄ in large-scale in this research.

The detailed morphology and structure of ZnFe₂O₄, ZnFe₂O₄-rGO, and Ag-ZnFe₂O₄-rGO were further characterized by SEM, TEM and HRTEM, as depicted in Fig. 2. ZnFe₂O₄ nanoflowers were first prepared by the hydrothermal method. Fig. 2A is a schematic diagram of the synthesis process of Ag-ZnFe₂O₄-rGO. Typical SEM and TEM images of the ZnFe-alkoxide precursor are shown in Fig. 2B and B[#]. The magnified FE-SEM image of the inset in Fig. 2B depicts that the thickness of nanosheets is 10–30 nm. Compared with the ZnFe-alkoxide, the morphology of the ZnFe₂O₄ products has obvious change after thermal treatment, and the products are composed of many uniform microspheres assembled by nanosheets (Fig. 2C and C[#]). Fig. 2D and D[#] provide representative images of the ZnFe₂O₄-rGO composite. It can be clearly seen that the rGO has been dispersed on the surface of the ZnFe₂O₄ and formed a good coating on it. From Fig. 2E and E[#], we can observe that the Ag-ZnFe₂O₄-rGO has pompon mum flower-like structure, with the size about 2–3 μm. Ag NPs were deposited on the surface of the large rGO sheets. Both the edge of rGO and the nanostructure of ZnFe₂O₄ nanoflowers and Ag NPs could be observed clearly in the TEM image of higher magnification (Fig. 2F). This strong mutual interaction among the ZnFe₂O₄, Ag NPs, and the graphene sheets enables rapid electron transport, thus guaranteeing efficient chemical performance. Based on the area-selected HRTEM images (Fig. 2E[#] and F), the (311) plane of ZnFe₂O₄ with a lattice spacing of 0.25 nm and phase metallic Ag (111) plane with a lattice spacing of 0.24 nm indicate them to be in an intimate interface contact, which is in favor of the charge separation.²³ This shows that a heterojunction was formed between ZnFe₂O₄ and rGO, as well as Ag NPs. As shown in Fig. 2H–L, the chemical compositions of Ag-ZnFe₂O₄-rGO were obtained through energy dispersive X-ray spectroscopy (EDS). Zn, Fe, O, C and Ag elements were detected in the selected range (the rectangular regions marked in Fig. 2G). Obviously, C and Ag elements were uniformly distributed on the surface of ZnFe₂O₄ without any significant aggregation (Fig. 2K and L).

The X-ray diffraction (XRD) patterns were characterized to check the phase structure of as-synthesized precursor, ZnFe₂O₄, Ag-ZnFe₂O₄, Ag-ZnFe₂O₄-rGO (Fig. 3). For these XRD patterns, the peaks at 30.3°, 35.8°, 43.3°, 53.9°, 57.2°, and 62.8° are indexed to the (220), (311), (400), (422), (511), and (440) crystal planes of spinel-type ZnFe₂O₄ (JCPDS 22-1012), respectively. For the ZnFe₂O₄-rGO, an additional weak broad peak is observed at 17–21°, which can be indexed to reduced graphene oxide. Bare



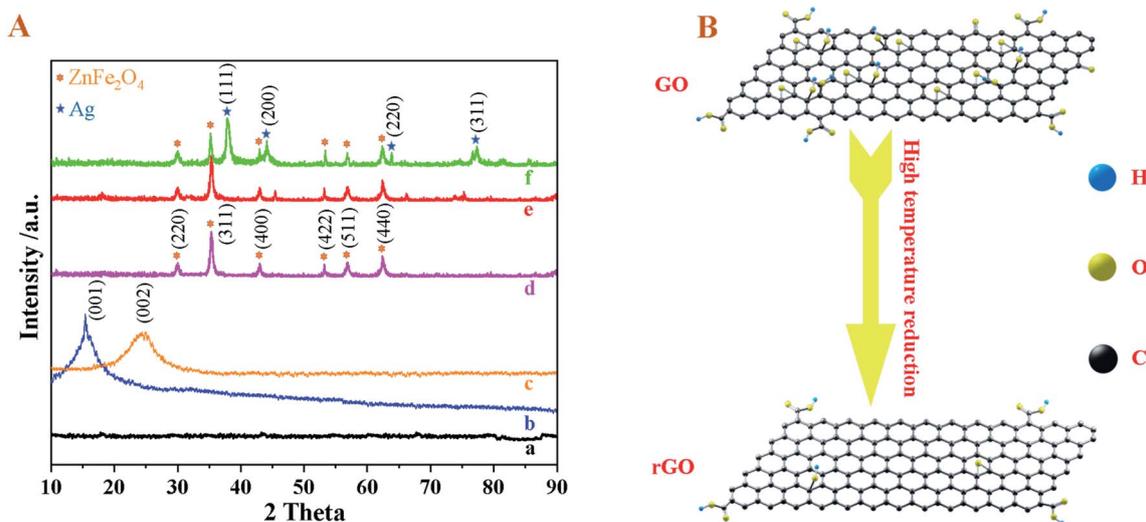


Fig. 3 (A) XRD pattern of (a) ZnFe-alkoxide precursor, (b) GO, (c) rGO, (d) bare ZnFe₂O₄, (e) ZnFe₂O₄-rGO, and (f) Ag-ZnFe₂O₄-rGO. (B) Schematic diagram of the reduction process of GO.

rGO exhibits its characteristic peak (002) at the 20–25°, but the XRD peak for rGO is not detected in the Ag-ZnFe₂O₄-rGO. This can be attributed to the effective minimization of the restacking of rGO sheets after reduction by anchoring Ag and ZnFe₂O₄ nanoflowers as spacers.³⁰ Moreover, additional XRD peaks at 38.06°, 44.22°, 64.42°, and 77.47° is assigned to the (111), (200), (220), and (311) crystal planes of Ag NPs (JCPDS 04-0783) in the Ag-ZnFe₂O₄-rGO.³¹ In addition, it is clear that the peak at 10.96° is attributed to (001) plane of GO. A broad peak at 24.60° is observed and the peak of GO is vanished in rGO, which suggests the GO was reduced mostly by heat treatment and rGO was prepared successfully. However, the diffraction peak of rGO crystal surface (002) disappears in that of the Ag-ZnFe₂O₄-rGO, which suggested that the ordered stacking of rGO layer was destroyed when the ZnFe₂O₄ nanoflowers and Ag NPs were loaded synchronously on rGO surface.³²

The surface electronic status and elemental composition of the Ag-ZnFe₂O₄-rGO nanocomposite can be seen on the X-ray photoelectron spectroscopy (XPS) in Fig. 4. The survey spectra (Fig. 4A.) reveals the presence of the Zn 2p, Fe 2p, Ag 3d, O 1s, and C 1s energy regions. It can be easily found in Fig. 4B that the high-resolution Zn 2p spectrum denoted two major fitting peaks centered at 1044.8 and 1021.7 eV, which are assigned to Zn 2p_{1/2} and Zn 2p_{3/2}, respectively, confirming about the existence of Zn(II) oxidation state in the ZnFe₂O₄.³³ In terms of the Fe 2p spectrum (Fig. 4C), the binding energies for Fe 2p_{3/2} at 713.1 and 711.4 eV correspond to the tetrahedral and octahedral sites, respectively. Moreover, the peak corresponding to a binding energy of 725.6 eV is in accordance with the Fe 2p_{1/2}, and the two shake-up satellite signals (at 719.3 and 732.8 eV) also indicate that only Fe³⁺ was present in the ZnFe₂O₄.³⁴ Eventually, these analyses confirm the Fe(III) oxidation state in the ZnFe₂O₄ sample.³⁵ The distinctive peaks of Ag (Fig. 4D) at binding energies of 368.1 and 374.4 eV are well ascribed as Ag-3d_{5/2} and Ag-3d_{3/2}, respectively. Astonishingly, the doublet of Ag-3d has

a fissure close to 6.0 eV, indicating the presence of metallic Ag in the Ag-ZnFe₂O₄-rGO.⁴ As represented in Fig. 4E, the O 1s spectrum can be divided into 3 different peaks at 530.4, 531.8 and 532.8 eV. The O 1s binding energy of 530.4 eV is assigned to the Fe-O and Zn-O. Meanwhile, the peaks with binding energies of 531.8 and 532.8 eV are assigned to the surface-absorbed oxygen species, and the presence of residual oxygen-containing groups bonded with carbon in graphene (sun as C=O and C-O), respectively.³⁶ The chemisorbed oxygen on the Ag-ZnFe₂O₄-rGO surface is the most active oxygen, which plays a part and parcel role in the oxidation reaction.³⁷ As shown in the high resolution XPS spectra of C 1s (Fig. 4F), the peaks at 288.5, 285.3, and 284.5 eV are due to the C in C=O, C-O, and C=C/C-C. Obviously, it can be seen that the intensity of C=O and C-O are lower than C-C and C=C, which indicates that oxygen-containing groups in GO has been reduced by high temperature heat treatment.³⁸ A schematic diagram of the heat treatment process is depicted in Fig. 3B. Based on what has been mentioned above (EDS, XRD, and XPS analysis), the Ag-ZnFe₂O₄-rGO composites were successfully synthesized *via* a facile hydrothermal approach, followed by a photo-reduction process.

FT-IR analysis was used to confirm the functionalization of the synthesized photocatalyst. Fig. 5A and S3† reveal the FT-IR spectra of the as-obtained samples. The peaks of GO that appearing at 1051, 1230, 1420, 1614, and 1735 cm⁻¹ are assigned to C-O stretching vibration from alkoxy groups, C-O stretching vibration of epoxide, O-H stretching vibration of carbonyl, conjugate C=C skeletal stretching vibration of unoxidized graphite domains or the remaining sp² C character of graphite, and C=O stretching vibration of carbonyl and carbonyl groups, respectively. For rGO, the absence of most bands related to the above oxygen-containing functional groups demonstrates that the GO was reduced mostly by high temperature heat treatment. Further, the peak at 1590 cm⁻¹ is



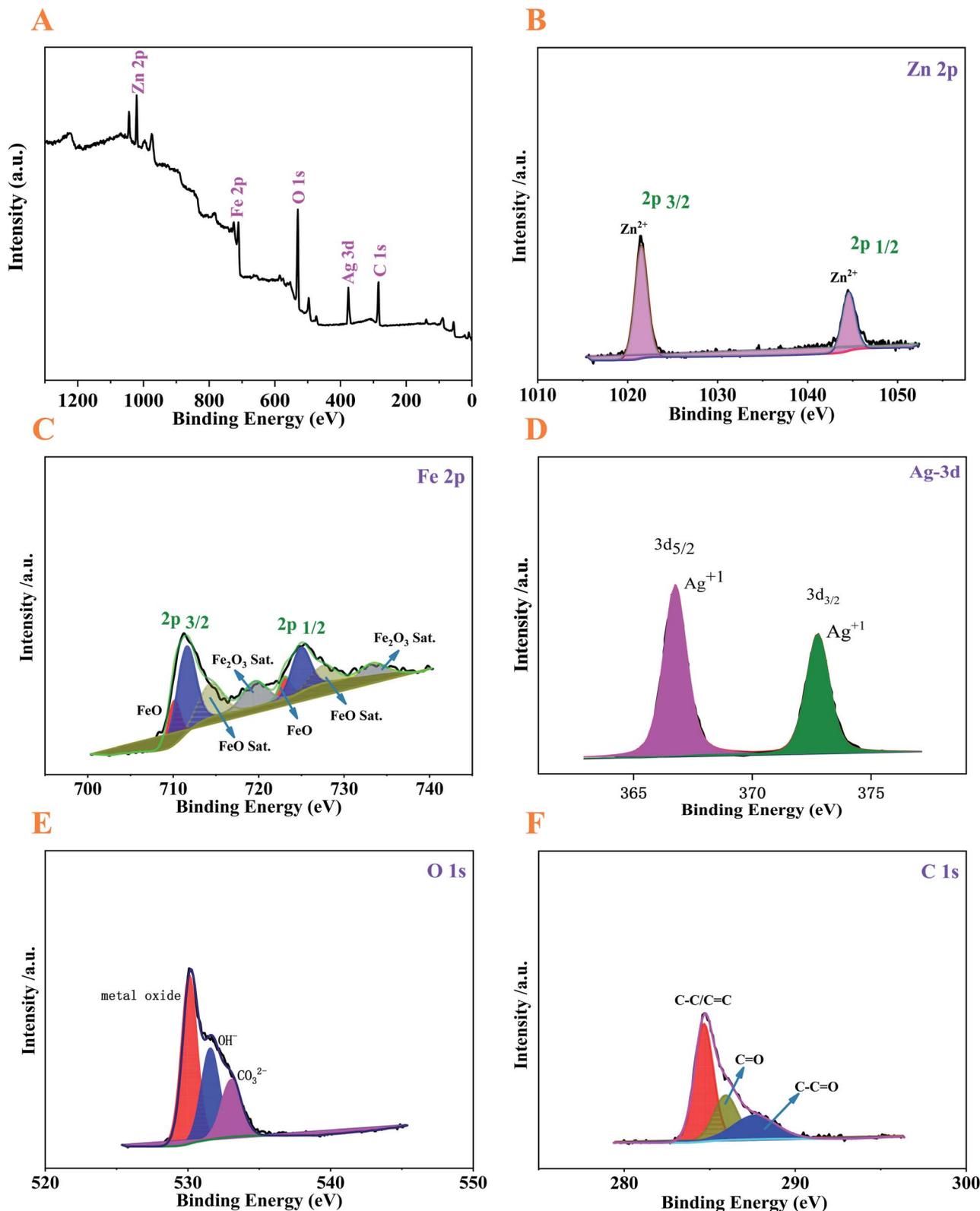


Fig. 4 XPS of the Ag-ZnFe₂O₄-rGO nanocomposite: (A) survey scan spectrum and sub-spectra of (B) Zn 2p, (C) Fe 2p, (D) Ag 3d, (E) O 1s, and (F) C 1s.

attributed to the conjugate C=C skeletal stretching vibration of graphite.^{28,33} The presence of broad absorption bands at 1650 and 3410 cm⁻¹ are the contribution from the vibration of O-H

group of adsorbed organic residues and water on the surface of ZnFe₂O₄, respectively.³⁹ Interestingly, FT-IR spectra of ZnFe₂O₄-rGO exhibits one characteristic peak around 910 cm⁻¹, which

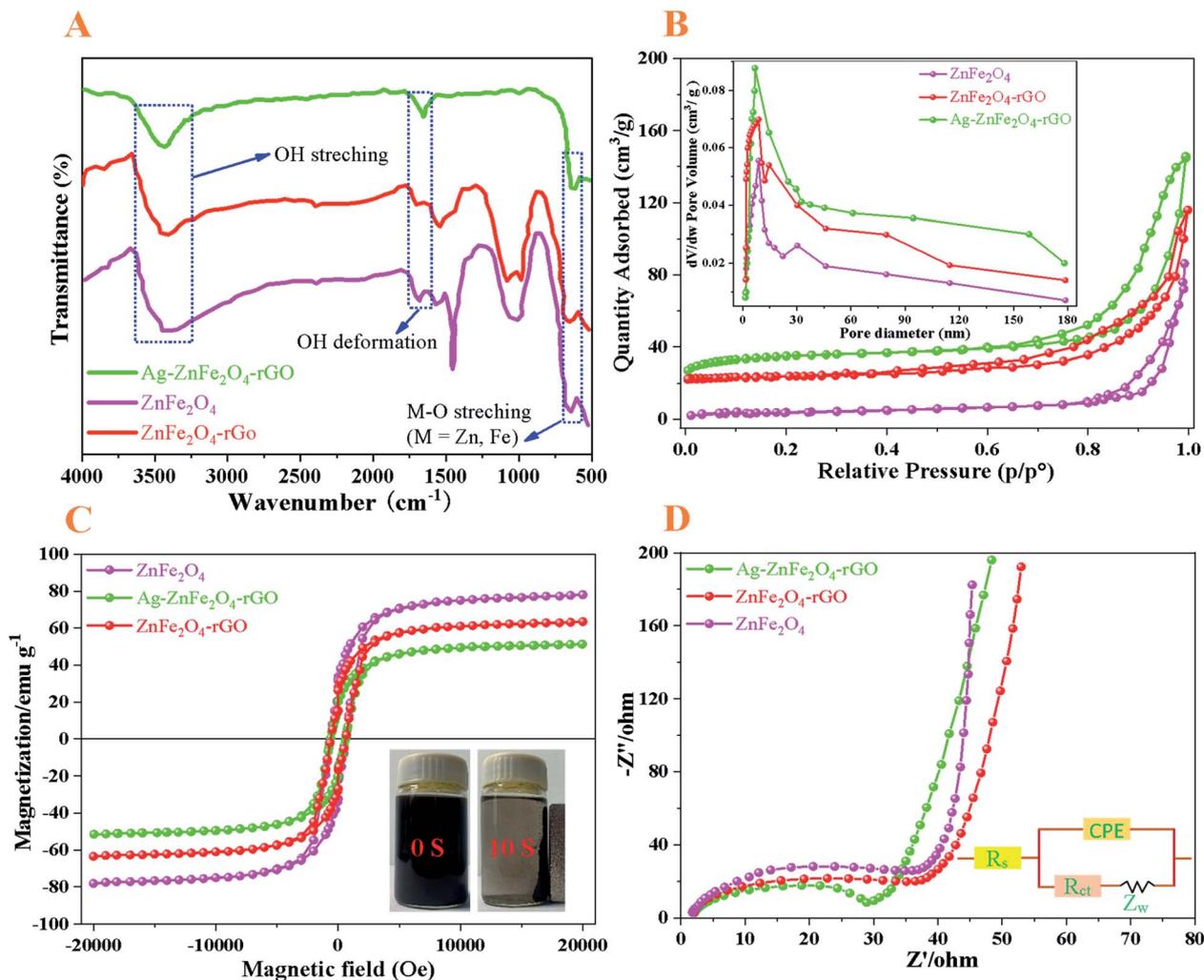


Fig. 5 (A) FT-IR spectra, (B) nitrogen adsorption–desorption isotherm, (C) M–H curves, and (D) EIS of the ZnFe_2O_4 , $\text{ZnFe}_2\text{O}_4\text{-rGO}$, and $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$, respectively. Insert of (B) shows the pore diameter distribution of its relative samples. The inset of (C) is the magnetic separation photograph of the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$. The inset of (D) shows equivalent circuit diagram of the photo electrochemical cell.

corresponds to C–O stretching of peroxide group. In addition, the FT-IR spectrum of $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ exhibits the main characteristic peaks of Fe–O and Zn–O bonds at $590\text{--}450\text{ cm}^{-1}$ and ZnFe_2O_4 at 1650 and 3410 cm^{-1} , confirming the spinel structure of zinc ferrite.⁴⁰

The porosity and specific surface area of ZnFe_2O_4 , $\text{ZnFe}_2\text{O}_4\text{-rGO}$ and $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ products were further investigated by N_2 adsorption–desorption analysis, as depicted in Fig. 5B. According to the IUPAC classification, the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ exhibits the type-IV isotherm with a hysteresis loop in the relative pressure range of $0.4\text{--}1.0$, suggesting the existence of abundant mesopores in the catalyst sample. The Brunauer–Emmett–Teller (BET) specific surface area (SBET) of ZnFe_2O_4 , $\text{ZnFe}_2\text{O}_4\text{-rGO}$, and $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ were calculated to be 32.53 , 78.01 , and $131.25\text{ m}^2\text{ g}^{-1}$, respectively. The inset of Fig. 5B presents the corresponding Barrett–Joyner–Halenda (BJH) pore size distribution (PSD) of the ZnFe_2O_4 , $\text{ZnFe}_2\text{O}_4\text{-rGO}$, and $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$, showing a sharp maximum at approximately 8.66 , 9.09 and 7.03 nm , respectively, further

confirming the mesoporous nature of the as-obtained nanocomposite.⁴¹ During the photocatalytic reaction, more adsorption–desorption and reaction sites can be provided through the larger surface area, leading to the improvement in photocatalytic activity.

Equally importantly, the magnetic property of photocatalysts is very useful for the separation of photocatalysts from solution after reaction by external magnetic field. In Fig. 5C, it is unveiled that the ZnFe_2O_4 and $\text{ZnFe}_2\text{O}_4\text{-rGO}$ have a ferromagnetic behavior, and the saturated magnetization (M_s) is 78.25 and 62.97 emu g^{-1} , respectively. When combining $\text{ZnFe}_2\text{O}_4\text{-rGO}$ and Ag NPs together, the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ still demonstrates strong ferromagnetic character with the M_s of 50.89 emu g^{-1} at room temperature. By comparing the M_s values of ZnFe_2O_4 and $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$, assuming that the net magnetic moment of ZnFe_2O_4 doesn't change ($= 78.25\text{ emu g}^{-1}$) before and after coating Ag-rGO, the mass ratio of ZnFe_2O_4 and Ag-rGO can be estimated to be $2.85 : 1$.⁴² Besides, due to the strong ferromagnetic property, the $\text{Ag-ZnFe}_2\text{O}_4\text{-rGO}$ photocatalyst can



easily be collected from solution within 10 s using a magnet as shown in the inset of Fig. 5C. The acceptable magnetic power of Ag-ZnFe₂O₄-rGO can lead to its rapid and easy separation from contaminated solutions. Fast and easy separation ability from contaminated solution is considered as an advantage of photocatalyst.^{43,44}

3.2 Photocatalytic performance analysis of Ag-ZnFe₂O₄-rGO photocatalyst

For a better understanding of the charge separation and transport mechanisms of the Ag-ZnFe₂O₄-rGO, the photocatalysts were examined using electrochemical impedance spectroscopy (EIS). The order of the arc radius of these materials is roughly ZnFe₂O₄ < ZnFe₂O₄-rGO < Ag-ZnFe₂O₄-rGO. In connection, the lesser arc radii in the impedance spectra indicates lower separation and transfer efficiency at the photocatalysts. One of the important roles of rGO is its ability to act as an electron acceptor and transfer channel to facilitate the

separation and migration of photo-generated e⁻.⁴⁵ The electrochemical impedance graphs for all photocatalysts are given in Fig. 5D, where the radius of the semicircle in the EIS plot became smaller with the introduction of rGO and Ag NPs, indicating that the Ag-ZnFe₂O₄-rGO discloses the least electron transfer resistance. Additionally, for Ag-ZnFe₂O₄-rGO samples, the transfer of e⁻ and h⁺ at the interface between the electrode and electrolyte is facilitated, and Ag-ZnFe₂O₄-rGO with the smallest arc radius illustrates the fastest separation and transfer of photo-generated e⁻ and h⁺. Remarkably, both the electron-accepting and transport properties of graphene in the Ag-ZnFe₂O₄-rGO nanocomposite can contribute to the suppression of charge recombination. Therefore, a higher rate of photocatalysis would be achieved.

To further investigate the intrinsic reasons behind the superior photodegradation performance of the diffuse reflectance spectra (DRS) were used to measure the energy band structure. For this purpose, the results are given in Fig. 6A. The band gap (E_g) energies of the sample were measured by

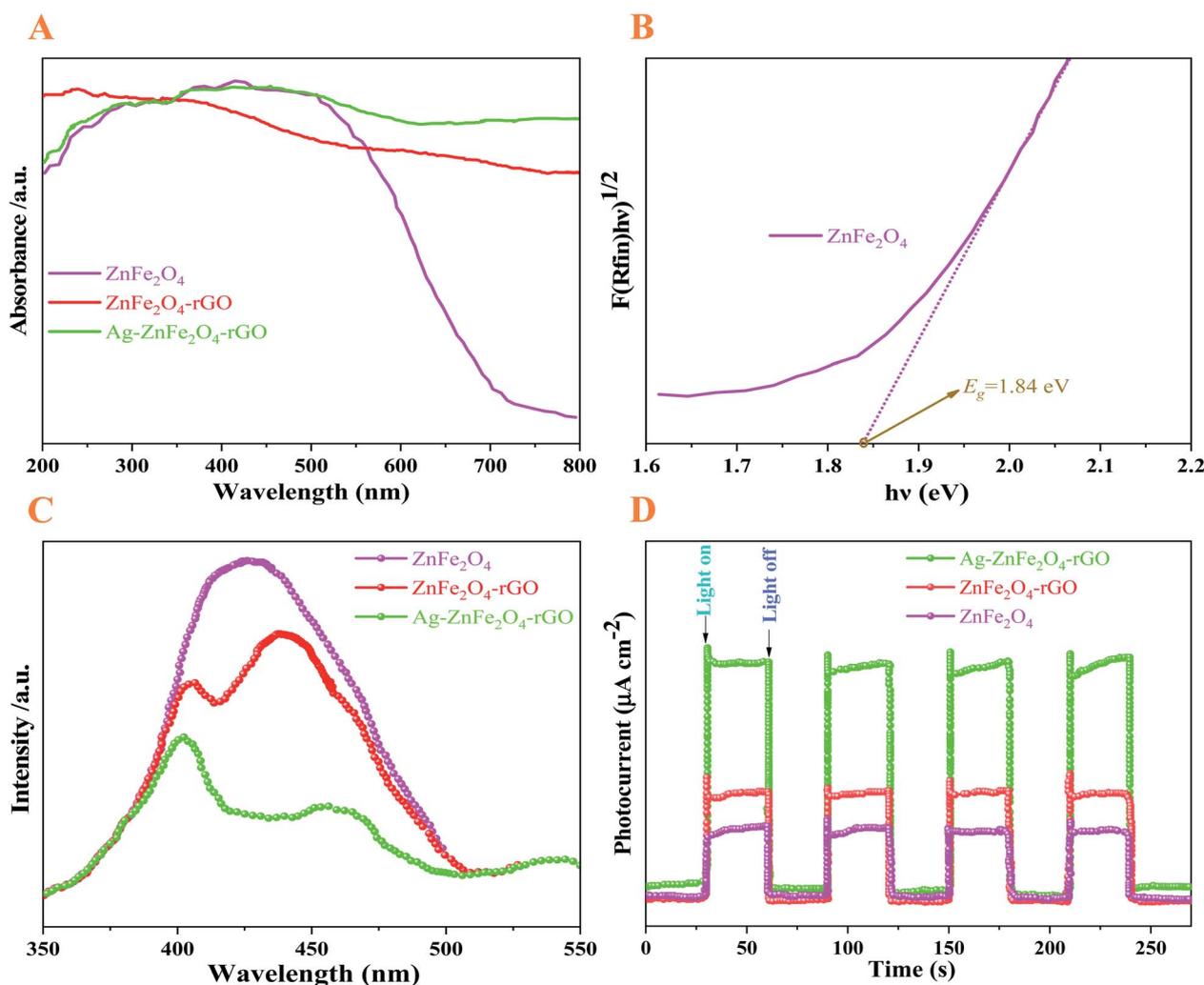


Fig. 6 The photophysical properties of the ZnFe₂O₄, ZnFe₂O₄-rGO, and Ag-ZnFe₂O₄-rGO materials. (A) UV-vis diffuse reflectance spectra, (B) indirect energy band gap evaluation from the plots of $(F(R) \times hv)^{1/2}$ versus the hv , (C) room-temperature PL emission spectra, and (D) photocurrent transient response of the ZnFe₂O₄, ZnFe₂O₄-rGO, and Ag-ZnFe₂O₄-rGO.



transforming the diffuse reflectance spectrum into the equivalent absorption coefficient that is proportional to the Kubelka-Munk (KM) function $F(R)$ (eqn (5)):²⁷

$$F(R) = \frac{(1 - R)^2}{2R} = \alpha \quad (5)$$

where R is reflectance measured from an infinity thick layer of a sample ($R = R_{\text{sample}}/R_{\text{standard}}$), and α represents the photon energy and absorption coefficient. The band gap energies were obtained from the plots of $(\alpha h\nu)^{1/n}$ versus the $h\nu$ curve as the intercept of the extrapolated linear part of the plot at $(\alpha h\nu)^{1/n} = 0$. Herein, h = planck's constant, and ν = the light frequency. n describes the optical transition of the photocatalyst, $n = 0.5$ for a direct type transition (such as ZnFe_2O_4 , C_3O_4) and $n = 2$ for an indirect type transition (TiO_2). Fig. 6B plots the $(\alpha h\nu)^2$ versus the $h\nu$ curve. The value of the band gap energy (E_g) can be obtained by extrapolating the linear part of the curve to the horizontal axis ($h\nu$ axis). The indirect type transition shows band gap values of 1.84 eV for ZnFe_2O_4 .⁴⁶

In the bare ZnFe_2O_4 , Fe cations are highly sensitive to light and absorb a wide range of light extending from 200–700 nm, corresponding to a band gap of approximately 1.84 eV. The introduction of rGO increases the absorbance intensity of the composites substantially. The enhancement of visible-light absorption for the nanocomposites is caused mainly by the background absorption of rGO, as well as by the SPR effect of Ag NPs.⁴⁷ Extraordinarily, the intense visible-light absorption of the photocatalyst is mainly due to the metal charge transfer transitions as proposed by Hart *et al.*⁴⁸ It is important to know the electrons from rGO are captured by Fe^{3+} in the ZnFe_2O_4 to form Fe^{2+} , the Fe^{2+} will continue react with the dissolved O_2 to generate Fe^{3+} . The increase in light absorption behavior of rGO composite is attributed to the efficient separation of interlayer spacing of aromatic rings in graphene oxide and black body property.⁴⁹ Therefore, a greater amount of visible-light was absorbed and played an important role in the generation of more charge carriers in the photocatalyst and hence better catalytic activity. Interestingly, the results of UV-vis spectra indicated that Ag– ZnFe_2O_4 –rGO denoted a red shift with broad light absorbance range, which was beneficial to the higher photocatalytic performance in photocatalytic degradation reaction.⁵⁰

The room-temperature photoluminescence (PL) emission spectra gave details about the recombination, migration, and shifting of photo-generated charge carriers. The higher PL intensity indicates higher recombination efficiency of photo-generated e^- and h^+ . As is graphically depicted by the Fig. 6C, the PL emission intensity decreased in the following order: pure $\text{ZnFe}_2\text{O}_4 > \text{ZnFe}_2\text{O}_4$ –rGO $>$ Ag– ZnFe_2O_4 –rGO. With introduction the rGO and Ag NPs in ZnFe_2O_4 heterojunctions, the PL intensity declined, and Ag– ZnFe_2O_4 –rGO shows the lowest PL intensity, which unveils a direct and strong interaction between ZnFe_2O_4 and carbon materials. The formed composite exhibits better charge separation compared to neat ZnFe_2O_4 because the photo-excited e^- are trapped and channelized in the p skeleton of the added carbon precursor causing better separation.⁵¹ It is clearly observed that ZnFe_2O_4 , with being modified by rGO,

displays very low PL signal intensity, suggesting delay the recombination of h^+/e^- and more charge transfer properties. Moreover, in a restricted volume, quantum confinement of the charge carriers of ZnFe_2O_4 due to size-related quantization may be responsible for the strong emission peaks. This effect may be ascribed to the electron-channelizing capacity of rGO; it traps the photo-excited electrons of ZnFe_2O_4 on its π skeleton and reduces the recombination rate of h^+/e^- . As a result, the recombination rate of h^+/e^- pair is suppressed, and the charge separation increases in the Ag– ZnFe_2O_4 –rGO.⁵² Therefore, Ag– ZnFe_2O_4 –rGO is likely to achieve first-rate photocatalytic activity toward the degradation of antibiotics. Further, the above claim manifest good correlation with EIS and photocatalytic result discussed in respective sections.

Under the irradiation of a 300 W Xe lamp that provided simulated solar light radiation (100 mW cm^{-2}), photocurrent curves were acquired by linear sweep voltammetry (LSV) scans under chopped illumination with a fixed time interval. As shown in Fig. 6D, the photocurrent responses of the hybrid nanoflowers showed cyclic alternations along with the on–off control of light. All electrodes exhibit excellent photocurrent reproducibility, suggesting that the samples were stable under the light switch cycle and the light response was reversible.³¹ Additionally, the photocurrent density of the Ag– ZnFe_2O_4 –rGO samples are all significantly higher than that of ZnFe_2O_4 , proving that the combination of rGO and ZnFe_2O_4 nanoflowers could lead to higher optoelectronic hole pair separation efficiency. This may attribute to the electric field on the interface between ZnFe_2O_4 and rGO, further confirming that the heterojunction was fabricated between ZnFe_2O_4 and rGO by coating rGO on the surface of ZnFe_2O_4 . It should be noted that a higher photogenerated current suggests a more efficient separation of photo-generated h^+/e^- pairs. This reveals that Ag– ZnFe_2O_4 –rGO stood out as the best photocatalyst among the series of samples. Consistent results were obtained in EIS studies under AM 1.5 G illumination. With all the analysis above taken into account, rGO and Ag NPs were more effective for the acceleration of interfacial charge transfer efficiency, thus improving the photocatalytic activity of the Ag– ZnFe_2O_4 –rGO.⁵³

3.3 Photocatalytic degradation activity of Ag– ZnFe_2O_4 –rGO

In this study, to measure the photocatalytic degradation activities of the obtained novel multicomponent heterojunctions with 3D flower-like structures, ENR solution was first applied to model antibiotics for photocatalytic degradation under visible-light ($\lambda = 465 \text{ nm}$) irradiation. It can be seen from Fig. 7, there is no obvious degradation for ENR without the presence of visible-light, indicating that light is necessary to initiate the photocatalysis. Under visible-light irradiation, using bare ZnFe_2O_4 as the photocatalyst, ENR was degraded by 78.92% after 30 min, respectively. Moreover, after the introduction of rGO, the photocatalytic degradation activity significantly increased to 86.36% (ENR) and within 30 min under visible-light irradiation, respectively. Similarly, by introducing the Ag NPs to the flower-like ZnFe_2O_4 –rGO, the photodegradation efficiency was enhanced to 98.68% (ENR) within 30 min under



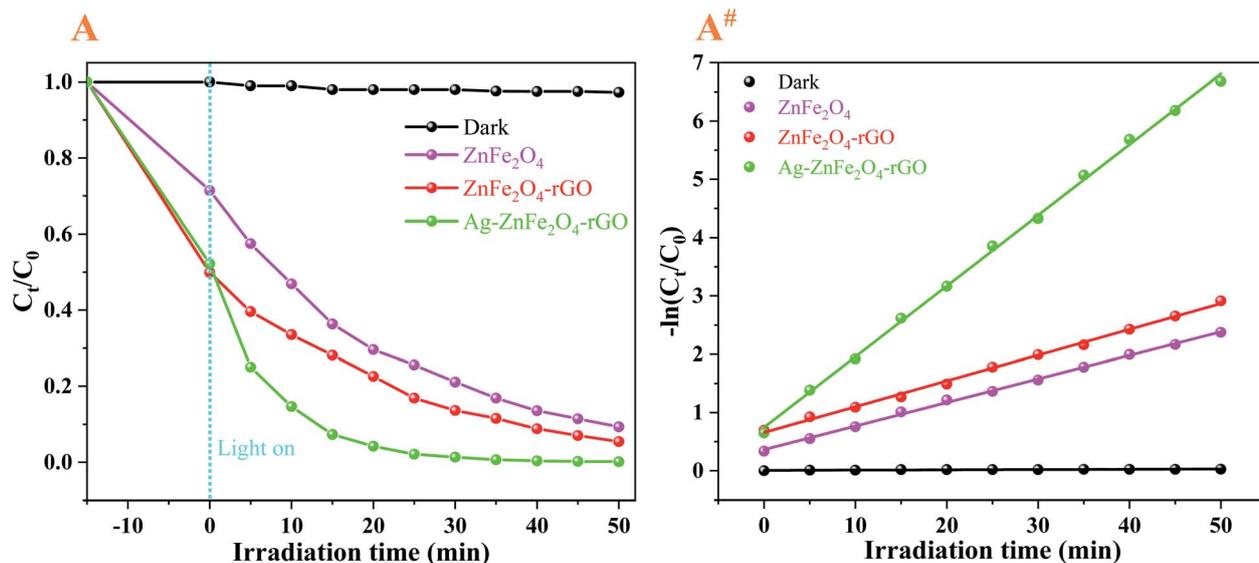


Fig. 7 Photocatalytic degradation of 10 mg·L⁻¹ ENR (A and A#) on as-prepared the ZnFe₂O₄, ZnFe₂O₄-rGO, and Ag-ZnFe₂O₄-rGO under visible-light ($\lambda = 465$ nm) irradiation for comparison, respectively.

visible-light irradiation, respectively. This phenomenon is mainly caused by the SPR effect of Ag NPs. Additionally, under the stimulation of visible-light radiation, photo-generated e⁻ can be quickly injected into the carbon layer of the rGO, and then react with the O₂ adsorbed on the surface of the rGO to generate [•]O₂⁻ radicals.²¹ Thus, the as-prepared Ag-ZnFe₂O₄-rGO photocatalyst can produce more photo-generated e⁻ and h⁺, as well as more superoxide anions. Due to the photo-generated e⁻, h⁺ and [•]O₂⁻, organic antibiotics can be oxidized and decomposed into H₂O, CO₂ and other products.⁵⁴ During the electron transfer process between semiconductor materials, the charge recombination in the Ag-ZnFe₂O₄-rGO is inhibited, and the photocatalytic degradation efficiency is greatly improved.

3.4 Photocatalytic degradation reusability and stability

Fig. 8 and S4† demonstrate the photodegradation suitability of the as-obtained Ag-ZnFe₂O₄-rGO photocatalyst for antibiotics ENR under visible-light irradiation. The relationship between the concentration of ENR and the photodegradation time and the number of cycles illustrate that the degradation of ENR was faster when Ag-ZnFe₂O₄-rGO photocatalyst were used. Simultaneously, ENR could be degraded completely within 35 min under visible-light, respectively. Beyond any dispute, the stability and recyclability of photocatalysts are important parameters for their industrial and large-scale application. For this purpose, photocatalysts were collected after each degradation process and washed with 20 mL ethanol solution for 2 h then dried in an oven at 60 °C overnight, and used for the next run (Fig. S5†). After 10 repeated cycles of usage, the photodegradation efficiencies of Ag-ZnFe₂O₄-rGO to ENR remained at 37.64% within 50 min, respectively. It can be seen that the composite material synthesized in this study has a very superior reusability. In order to prove the photostability of Ag-ZnFe₂O₄-

rGO, a reusability experiment was carried out. It has been clear that after 10 cycles of degradation, a small decrease in XRD peak intensity was observed (Fig. S6†), which results in a slight reduction in photocatalytic activity. Additionally, in order to further confirm the photocatalyst morphological structure change during photocatalytic degradation process, the Ag-ZnFe₂O₄-rGO was imaged by the SEM after each degradation. The details are as Fig. 9. It can be clearly found that the photocatalyst after 8 cycles, the sample morphology has hardly

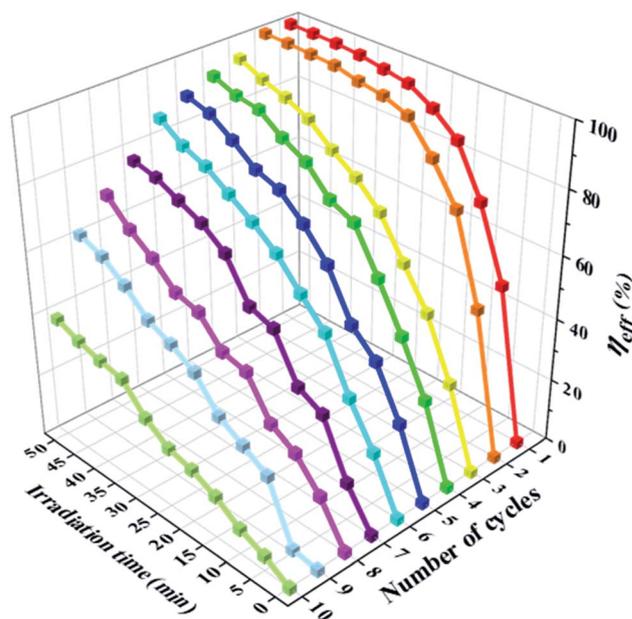


Fig. 8 Photodegradation rates curves for ENR (10 mg·L⁻¹) aqueous solution using Ag-ZnFe₂O₄-rGO photocatalysts for 10 cycles under visible-light irradiation.



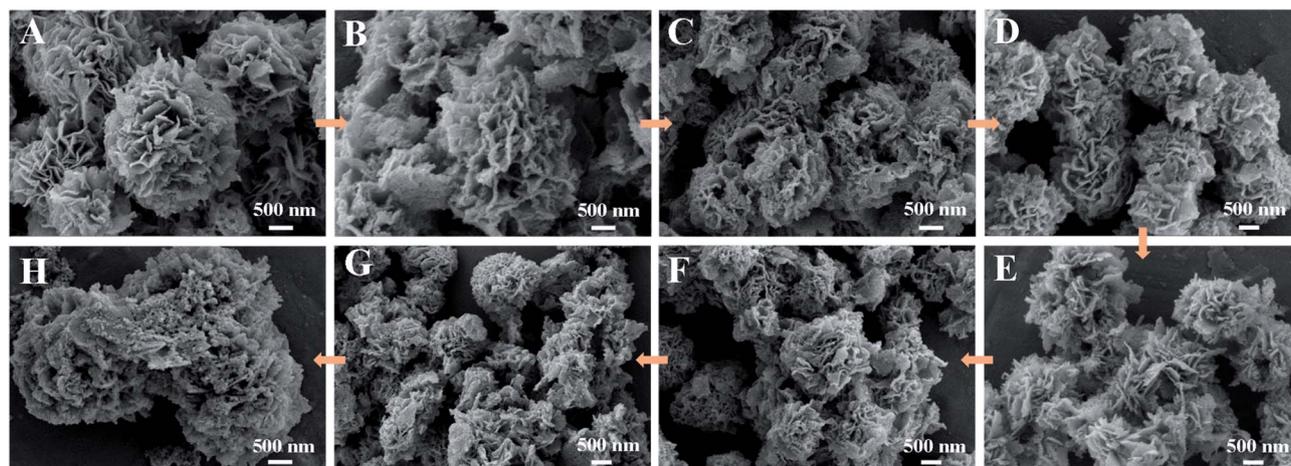


Fig. 9 (A), (B), (C), (D), (E), (F), (G), and (H) are SEM images after cyclic degradation of 1, 2, 3, 4, 5, 6, 7, and 8 times by the Ag-ZnFe₂O₄-rGO, successively.

significant change. Nevertheless, after 8 cycles, the morphology and structure of the Ag-ZnFe₂O₄-rGO sample changed significantly, almost no longer maintaining the original 3D flower-like structure. In general, the structure of the as-obtained Ag-ZnFe₂O₄-rGO is relatively stable. Most importantly, several studies have depicted that the photocatalytic degradation is a surface-mediated reaction and the photocatalytic efficiency and rate is highly dependent on the active sites onto the photocatalyst.⁵⁵ The 3D flower-like Ag-ZnFe₂O₄-rGO photocatalyst synthesized in this study has a larger surface area and dense reaction sites, and therefore the photocatalytic degradation performance is greatly improved. Some recently published contributions related to this are given in Table S1.† To take it a step further, according to the eqn (3), the photodegradation reaction rate constant (k_{pfo}) can be calculated to be 0.1212 min⁻¹ for ENR under visible-light.

3.5 Proposed photocatalytic mechanism of the Ag-ZnFe₂O₄-rGO

To further confirm the main active species, electron spin resonance (ESR) technology with 5,5-dimethyl-1-pyrroline *N*-oxide (DMPO) to detect the generation of $\cdot\text{O}_2^-$ and $\cdot\text{OH}$. The ESR-DMPO experiments were carried out in the dark and under irradiation for 10 or 15 min. In the dark conditions, no obvious signals for both $\cdot\text{O}_2^-$ and $\cdot\text{OH}$ could be detected in Fig. S7.† In Fig. S7B†, the DMPO- $\cdot\text{O}_2^-$ peaks were observed under visible-light irradiation, indicating that $\cdot\text{O}_2^-$ are produced. Furthermore, the characteristic peaks of DMPO- $\cdot\text{OH}$ and DMPO- $\cdot\text{O}_2^-$ were detected and the signal strength increased with the increase of irradiation time. The ESR experiment was carried out under different solutions, indicating that $\cdot\text{OH}$ was formed by the $\cdot\text{O}_2^-$ and $\cdot\text{HO}_2$ but not directly oxidized ENR in the degradation process.³⁴ Correspondingly, the conduction band

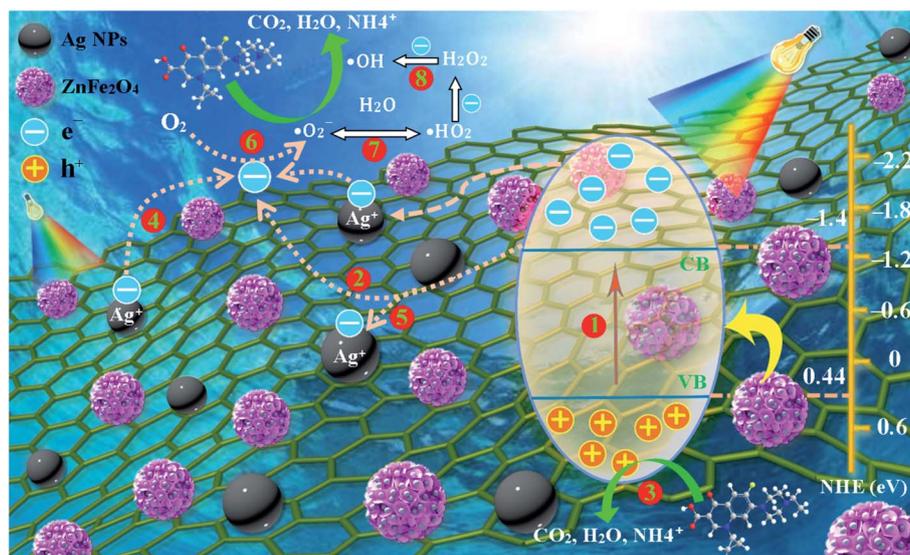


Fig. 10 Schematic diagram of the possible photocatalytic mechanism of Ag-ZnFe₂O₄-rGO composite under visible-light irradiation.



(CB) potential (E_{CB}) and valence band (VB) potential (E_{VB}) can also be calculated by the following formulas:^{56,57}

$$E_{VB} = X - E_c + 0.5E_g \quad (6)$$

$$E_{CB} = E_{VB} - E_g \quad (7)$$

where X is the absolute electronegativity of the semiconductor, that is, the geometric mean of the absolute electronegativity of the atoms in the semiconductor ($X_{Zn} = 4.45$ eV, $X_{Fe} = 4.06$ eV, $X_O = 7.54$ eV). After calculation, $X_{ZnFe_2O_4} = 5.86$ eV. E_c and E_g are the energy of free electrons on the hydrogen scale (4.5 eV) and the band gap values of the semiconductor, respectively. Therefore, the E_{VB} and E_{CB} of the $ZnFe_2O_4$ were estimated to be approximately +0.44 and -1.4 eV.

With the analysis above taken into account, the reasonable reaction mechanism for improving the photocatalytic activity can be offered by Fig. 10. First, through the e^- channelization ability of the rGO, the photo-excited e^- of $ZnFe_2O_4$ are trapped on its π framework, and the recombination rate of photo-excited h^+/e^- is prevented, forming a stable heterojunction between Ag and $ZnFe_2O_4$, as well as rGO. It is generally known that the CB ($E_{CB} = -1.4$ eV) and VB ($E_{VB} = +0.44$ eV) of the $ZnFe_2O_4$. Upon visible-light irradiation, e^- in the VB of $ZnFe_2O_4$ can be photo-excited to its CB to produce the h^+/e^- pairs after the irradiation of visible-light (pathway 1). Owing to the fact that the CB of the rGO (-0.75 eV) is more positive than that of the $ZnFe_2O_4$ (-1.44 eV) (pathway 2), the partial photo-generated e^- from CB of $ZnFe_2O_4$ are transferred to the surface of the rGO layers. Oppositely, the photo-generated h^+ left the VB of $ZnFe_2O_4$, which can prohibit the recombination of h^+/e^- pair. Thus, the photo-generated e^- and h^+ can be effectively separated. Meanwhile, the rGO also plays an important role in ternary composite. First of all, the unique structure of rGO provides the Ag- $ZnFe_2O_4$ -rGO with a larger surface area which can make photocatalyst absorb more light radiation and ENR. Moreover, there are a lot of defects and few excited groups containing oxygen in the rGO surface because of the reduction of GO, which can bring strong absorption capacity for the Ag- $ZnFe_2O_4$ -rGO. Finally, the conjugated p-system of rGO can also hinder the recombination of h^+/e^- pairs. Therefore, the coupling of $ZnFe_2O_4$ and rGO can effectively reduce the recombination rate of e^- and h^+ , and subsequently decreases the internal resistance as well as enhances the interfacial charge transfer efficiency, which can be seen in the EIS spectra (Fig. 5D).⁵⁸ Furthermore, the reactive h^+ at the VB of $ZnFe_2O_4$ will

oxidize ENR directly, because the potential of the VB of $ZnFe_2O_4$ (0.44 eV) is more negative than the potential required to oxidize the adsorbed H_2O on the surface to $\cdot OH$ ($E^0(\cdot OH/H_2O) = 2.87$ eV) (pathway 3).³³ Meanwhile, Ag NPs can absorb light and generate electrons due to the SPR effect (Fig. 11), plasmon-induced electrons on the Ag NPs can flow to the CB of rGO rather than $ZnFe_2O_4$ (pathways 4), owing to the less negative CB bottom of graphene compared to that of $ZnFe_2O_4$, and Ag NPs can also accept electrons from the CB of the $ZnFe_2O_4$ for enhancing the charge separation. A portion of the CB electrons on $ZnFe_2O_4$ tends to shift to the positive-potential Ag^+ and changes some Ag^+ to Ag^0 (pathways 5), whereas the other electrons can be scavenged by O_2 in the water, resulting in superoxide anion free radicals ($\cdot O_2^-$) and peroxy ($\cdot HO_2$) radicals [$E^0(O_2/\cdot O_2^-) = 0.33$ V, and $E^0(O_2/\cdot HO_2) = 0.05$ V] (pathways 6 and 7), which are the main active species in the reaction with ENR.⁵⁹ Since the produced $\cdot O_2^-$ can be prolonging to more than 15 min (Fig. S7B[†]), the photocatalytic degradation efficiency and rate of ENR can be significantly enhanced under visible-light irradiation. In addition, the produced oxygen-containing radicals ($\cdot O_2^-$ and $\cdot HO_2$) can further react with electrons and protons to produce hydroxyl radicals ($\cdot OH$) (pathway 8).⁶⁰ However, in this study, $\cdot OH$ is not the main active species for photocatalytic degradation of ENR. Consequently, the separation efficiency of the photo-generated charge carriers is effectively improved at the interface of the nanocomposite, which allows more participation of h^+ in the photocatalytic reaction. Thus, the Ag- $ZnFe_2O_4$ -rGO photocatalyst has high photocatalytic activity. The reaction equations can be briefly depicted as follows:

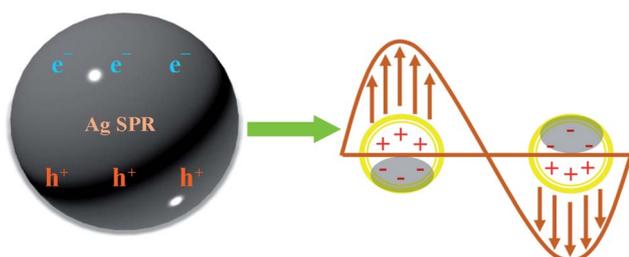
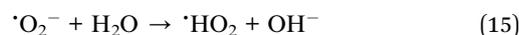
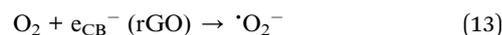
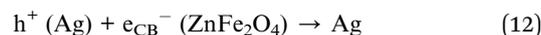
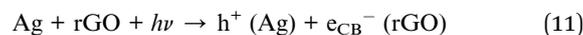
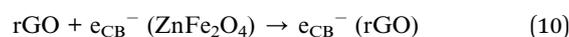
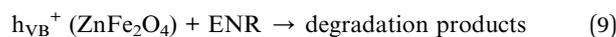
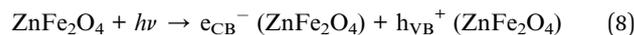


Fig. 11 Schematic diagram of the surface plasmon resonance (SPR) effect of Ag NPs.

3.6 Identified products on degradation of ENR

In order to explore the conversion pathway of ENR in the photocatalytic degradation process, the structures of eleven main photoproducts P1–P11 were identified by HPLC-Q-TOF-MS. For



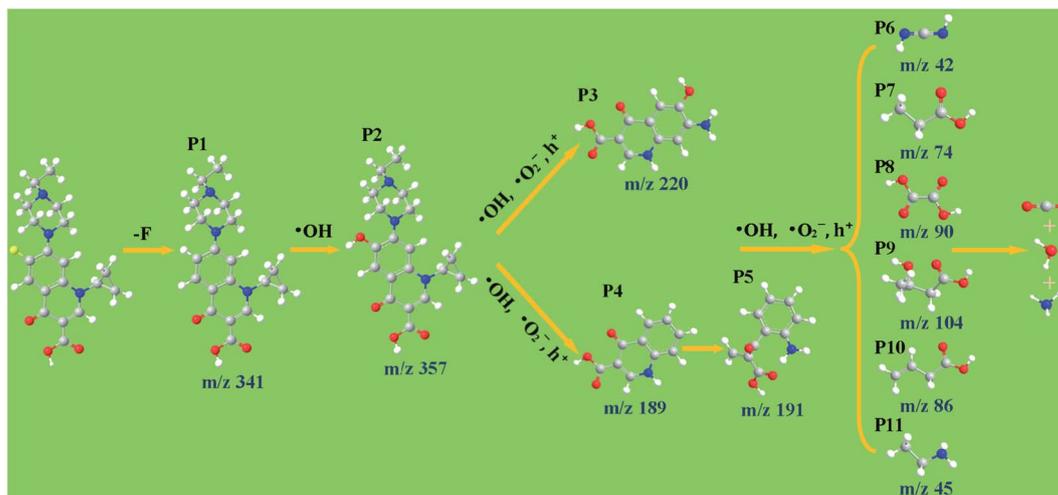


Fig. 12 Potential photocatalytic degradation pathways of ENR in the Ag-ZnFe₂O₄-rGO aqueous solution under visible-light irradiation.

the ENR, 11 organic intermediates were identified with the molecular weights and characteristic fragment ions shown in Table S2.† According to the experimental detection of the photodegradation intermediate and the theoretical calculation of the Fukui function, the degradation pathway of ENR in the Ag-ZnFe₂O₄-Ag photocatalytic process was proposed (Fig. 12). The details are as follows. First of all, the C-F bond of ENR was broken under the irradiation of UV-light (P1 ($m/z = 341$)), introducing the replaced -OH undergoing the attack of $\cdot\text{OH}$, and a typical product (P2 ($m/z = 357$)) for the fluoroquinolone oxidation was generated.⁶¹ For the product P2, on the one hand, N20 and C11 (Fig. S8†) were attacked by $\cdot\text{OH}$, $\cdot\text{O}_2^-$ and h^+ , leading to the formation of the P3 ($m/z = 220$). On the other hand, the cyclopropane and piperazine groups in the P2 detach to produce P4 ($m/z = 189$). Then, C8 in the intermediate P4 was further attacked by $\cdot\text{OH}$, $\cdot\text{O}_2^-$ and h^+ to form product P5 ($m/z = 191$). As a result, under the continuous attack of the reactive species, the quinolone ring and the benzene ring are destroyed and cleaved through a ring-opening reaction, and then *via* oxidation reactions to obtain smaller organic products (P7–P11). Finally, the intermediate products could be completely mineralized to CO₂, H₂O and NH₄⁺.

4. Conclusions

To conclude, Ag-ZnFe₂O₄-rGO photocatalysts were synthesized *via* a facile hydrothermal approach and heat treatment, followed by a photo-reduction process. The oxidation resistance of rGO could effectively maintain the structural and chemical stability of Ag-ZnFe₂O₄. Through the electron channelization ability of rGO, the photo-excited e^- of ZnFe₂O₄ were trapped on its π framework, and the recombination rate of e^-/h^+ was prevented, forming a stable heterojunction between Ag-ZnFe₂O₄ and rGO. The photocatalytic activity of Ag-ZnFe₂O₄-rGO was improved under visible-light. ENR were degraded completely within 35 min under visible-light illumination. Moreover, the photodegradation reaction rate constant (k_{pfo}) could be

calculated to be 0.1212 min⁻¹ for ENR. Heterojunctions between Ag and ZnFe₂O₄-rGO can effectively separate photo-generated carriers, and the high surface area of 3D flower-like ZnFe₂O₄ provides more reactive sites. The excellent conductivity of rGO facilitates rapid transfer of photoelectrons. Additionally, the *in situ* generated H₂O₂, h^+ and $\cdot\text{O}_2^-$ can degrade organic antibiotics through effective oxidation and mineralization. This research provides new ideas for the design and manufacture of heterojunction photocatalysts, as well as new ideas for environmental protection and sustainable development.

Conflicts of interest

There are no conflicts to declare.

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