Silver-Decorated Cobalt Ferrite Nanoparticles Anchored onto the Graphene Sheets as Electrode Materials for Electrochemical and Photocatalytic Applications

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ABSTRACT: The present work describes the synthesis of Ag-CoFe₂O₄/rGO nanocomposite as a photocatalyst through the hydrothermal process by the attachment of silver and cobalt ferrite (CoFe₂O₄) nanoparticles on the surface of reduced graphene oxide. The effect of Ag and reduced graphene oxide (rGO) on the structure, optical, magnetic, photocatalytic, and electrochemical performance of the CoFe₂O₄ is systematically explored through various analytical techniques. The analyses of the observed outcomes reveal that the graphene sheets are exfoliated and decorated with well-dispersed Ag and CoFe₂O₄ nanoparticles. UV–vis spectra indicate a gradual shift in the absorption edge toward the higher wavelength with the addition of Ag ions, which signifies variation in the energy gap of the samples. Photoluminescence results divulge that graphene can decline the electron–hole recombination rate and improve the photocatalytic activity of the Ag-CoFe₂O₄/rGO nanocomposite. In this context, the Ag-CoFe₂O₄/rGO sample presents good catalytic activity as compared to the CoFe₂O₄ and Ag-CoFe₂O₄ photocatalysts for the degradation of methylene blue (MB) dye and suggests that the rGO plays a vital role in the Ag-CoFe₂O₄/rGO nanocomposite. The deterioration rate of the samples is found to be in the order of CoFe₂O₄ (78.03%) < Ag-CoFe₂O₄ (83.04%) < Ag-CoFe₂O₄/rGO (93.25%) in 100 min for MB dye, respectively, under visible-light irradiation. The room-temperature ferromagnetic behavior of the samples is confirmed by the $M-H$ hysteresis loop measurements. Overall, the Ag-CoFe₂O₄/rGO nanocomposite promises to be a strong magnetic photocatalyst for contaminated wastewater treatment. The electrochemical performance of all of the samples was examined by the cyclic voltammetry (CV) that exhibits a superior rate performance and cycle stability of the Ag-CoFe₂O₄/rGO nanocomposite as compared to the other samples.

INTRODUCTION

Recently, microwave-absorbing materials have attracted much attention due to their inherent magnetic and electrical properties. Among the various microwave-absorbing materials, cobalt ferrite (CoFe₂O₄) is chosen for the present work owing to its unique structural, mechanical, thermal, physiochemical, and magnetic properties. The CoFe₂O₄ nanoparticles with a spinel structure have focused much attention because of their outstanding properties, such as high saturation magnetization, surface-area-to-volume ratio, and their shape- and size-dependent magnetic properties.1–4 Moreover, CoFe₂O₄ has been considered as promising candidates due to its high catalytic activity, a stable crystalline structure, low solubility, and excellent magnetic activity for simplifying the separation of catalysts from the reaction system.1–3 The doping with different metal ions (Zn, Co, Sr, and Gd) have been taken to improve the physiochemical properties of ferrite nanoparticles (NPs), which are essential for their potential applications in the field of photocatalysis,5–7 photodegradation of industrial dyes,11 and electrochemical energy storage materials.12 These doping ions with different levels are an easy way to influence the structural,13 optical,14 electrical,15 and magnetic properties.16 On the other hand, silver nanoparticles with their unique physical and chemical properties could significantly support and enhance photocatalytic and electrochemical performance.17,18 Additionally, the decoration of reduced graphene oxide (rGO) with ferrites such as CoFe₂O₄ nanoparticles exhibit attractive catalytic activities.19–21 Another unique advantage provided by the rGO is its high electron mobility, large surface area, good structural

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flexibility, and excellent electrical properties that can make CoFe2O4/rGO composite an ideal candidate for catalytic applications.

Apart from the materials, the synthesis process plays an important role in controlling the shape and size of the nanoparticles that considerably stimulate the physical properties. A variety of techniques including chemical routes such as sol–gel,22 co-precipitation,23 solvothermal,24 hydrothermal,25 and microemulsion26 have been reported so far for the synthesis of CoFe2O4 nanoparticles. Among various techniques, hydrothermal is one of the best convenient and versatile methods as it is simple, cost-effective, and useful for the preparation of ferrite nanoparticles. In the present study, Ag-CoFe2O4 nanocomposite supported on graphene sheets was successfully prepared by the one-pot solvothermal technique. The samples were characterized through powder X-ray diffraction (XRD), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), Fourier transform infrared (FTIR) spectroscopy, X-ray photoelectron spectroscopy (XPS), UV–vis spectroscopy, photoluminescence (PL) spectroscopy, vibrating sample magnetometer (VSM), and cyclic voltammetry (CV) techniques to study the physical properties of the compositions. Looking at the unique set of properties of CoFe2O4, the present investigation focuses on enhancing its photocatalytic and electrochemical properties by incorporating Ag and rGO in the matrix.

■ EXPERIMENTAL DETAILS

All chemicals were labeled as analytical grade and used as received. In a typical procedure, the CoFe2O4 nanoparticles were prepared using nitrates of Co(NO3)2·6H2O (Sigma-Aldrich, >99.999% purity) and Fe(NO3)3·9H2O (Sigma-Aldrich, >99.95% purity) and dissolved in 10 mL of distilled water. Then, 15 mL of sodium hydroxide was added to the solution. Thereafter, the solution was magnetically stirred at a constant stirring speed of 500 rpm for 60 min and transferred into a 50 mL Teflon-lined stainless steel autoclave and then kept at 200 °C for 16 h. In this way, a black powder was collected at the bottom of the container and washed with deionized water and ethanol several times and further dried in a vacuum at 80 °C. At the end, the product is ready for further characterization. The same method was repeated to prepare the Ag-decorated CoFe2O4 nanocomposite.

Synthesis of Ag-CoFe2O4/rGO Nanocomposite. Graphene oxide (GO) was synthesized from natural graphite via a modified Hummers method as described elsewhere.27 In a typical procedure, Ag-CoFe2O4/rGO nanocomposite was synthesized by adding 0.50 g of GO in 150 mL of deionized water and sonicated for 1 h to form a homogeneous solution. Then, 2.08 g of Fe(NO3)3·9H2O, 0.75 g of Co(NO3)2·6H2O, and 0.52 g of AgNO3 (Sigma-Aldrich, ≥99.0% purity) were added to the above suspension of GO and stirred for 30 min. The pH of the resulting mixture was adjusted to ~10 by adding 6 M NaOH solution and stirred for 30 min. After that, the solution was transferred to a Teflon-lined autoclave and heated to 180 °C for 18 h and then subsequently cool down naturally to ambient temperature. The obtained black product (i.e., Ag-CoFe2O4/rGO) washed with ethanol and water several times and dried at 60 °C for 12 h. Finally, the black precipitate was ground into powder for further characterization.

Characterization. The crystallographic information of the as-prepared samples was checked by the powered XRD patterns obtained by PANalytical XPert powder diffractometer having Cu Kα radiation (λ = 1.5406 Å, operating voltage 45 kV, and current 40 mA) at a step size of 0.02° and 2θ range of 20–90°. The particle size, crystallinity, and composition of the as-prepared samples were examined using field emission transmission electron microscope (FETEM) and high-resolution TEM (HRTEM) coupled with EDS using a Joel JEM-2100F TEM instrument operated at 200 kV. The XPS measurements were performed by a photoelectron spectrometer with Mg Kα source, a concentric hemispherical analyzer operating in a fixed-analyzer transmission mode, and a multichannel detector. The infrared spectra were registered in the vibrational frequency range from 400 to 4000 cm−1 using a JASCO 460 plus FTIR spectrometer. Magnetic hysteresis (M–H) loops were obtained through the VSM system at room temperature in an applied magnetic field sweeping from −10 000 to +10 000 Oe. The UV–vis absorption spectra were recorded by a Shimadzu UV-2450 spectrometer over the spectral range of 300–1100 nm. The room-temperature PL spectra of the samples were obtained using a Shimadzu UV–vis (UV-2550) spectrophotometer with a continuous wave laser operating at 340 nm having an excitation source of 350–600 cm−1. A Brunauer–Emmett–Teller (BET) method was employed to evaluate the surface area and pore size distribution by nitrogen gas absorption–desorption using an ASAP 2010 system at 77 K.

Electrochemical Measurements. Cyclic voltammetry (CV) measurements were carried out using a CHI 660E electrochemical workstation (Beijing, China). These measurements were made in an electrolyte of 0.5 M KOH using a conventional three-electrode system comprising a platinum wire as the counter electrode, a Ag/AgCl reference electrode, and a catalyst-modified glass carbon (3.0 mm) as the working electrode. To prepare the homogeneous ink, 2.5 mg of nanocomposites, 0.5 mL of Naion was dispersed in a few drops of propanol, and then the mixture was ground. The prepared ink was placed onto the surface of the glassy carbon electrode (GCE), which was dried at 60 °C temperature.

Photocatalytic Activity Measurements. To assess the photocatalytic activity of the samples, the degradation of methylene blue (MB) dye under visible-light irradiation was examined using a 300 W xenon lamp (λ = 400 nm). In all degradation experiments, 50 mg of the photocatalyst was dispersed in the MB solution (10 mg/L, 80 mL) and then placed in the dark with continuous stirring for 1 h to reach an adsorption–desorption equilibrium between the dye and the catalyst. At a fixed time interval, 5 mL of aliquots was withdrawn from the suspension and then magnetically separated to remove essentially all of the catalysts. The photocatalytic degradation efficiency was measured using a Shimadzu UV–vis (UV-2550) spectrophotometer to determine the degradation of MB dye in the solution.

■ RESULTS AND DISCUSSION

Structural Studies. The phase purity and crystallinity of the Ag nanoparticles, Ag-CoFe2O4 and Ag-CoFe2O4/rGO nanocomposites were examined through powder XRD patterns and the results are displayed in Figure 1. The peaks at the diffraction angles (2θ) ~30.6, 35.5, 43.5, 44.6, 53.8, 57.4, 62.7, 64.6, 71.6, 74.5, and 77.6° assigned to the (220), (311), (400), (331), (422), (511), (440), (531), (620) (533), and (444) crystal planes of CoFe2O4 (CFO), respectively, which are consistent with the standard data of the face-centered cubic of
CoFe$_2$O$_4$, the nanoparticles are slightly agglomerated and CoFe$_2$O$_4$/rGO nanocomposites, which are well-matched with Ag and minor impurities (*some additional peaks associated with the crystal structure of particles and the Ag-CoFe$_2$O$_4$/rGO nanocomposite were"

nanoparticles of CoFe$_2$O$_4$ and Ag are well-connected with the lies in the range of 35 nanosheets in a dense form and the average particle diameter dispersion of Ag-CoFe$_2$O$_4$ onto the surface of the rGO positions to ensure a uniform distribution of the elements and adhesion between rGO and nanoparticles. To ensure the microstructure of the CoFe$_2$O$_4$ nano-

"morphology and internal structure of the CoFe$_2$O$_4$ nano-
no-

"particles and the Ag-CoFe$_2$O$_4$/rGO nanocomposite were investigated through FETEM and high-resolution TEM (HRTEM) images and displayed in Figure 2a–c. In CoFe$_2$O$_4$ the nanoparticles are slightly agglomerated and have a spherical shape with an average diameter of ~34 nm (Figure 2a). However, the TEM image in Figure 2b exhibits that Ag-CoFe$_2$O$_4$ are decorated on the surface of rGO nanosheets in a dense form and the average particle diameter lies in the range of 35–46 nm. These results are consistent with the XRD data analysis. It is interesting to note that the nanoparticles of CoFe$_2$O$_4$ and Ag are well-connected with the graphene sheets; even a sonication process was carried out for the preparation of TEM grids, leading to an exceptional adhesion between rGO and nanoparticles. To ensure the microstructure of the CoFe$_2$O$_4$ particles on the surface of rGO, HRTEM image is captured and shown in Figure 2c. The values of the interplanar spacing (d-spacing) of the cubic spinel crystal of CoFe$_2$O$_4$ and Ag are estimated to be 0.297 and 0.235 nm, respectively, and shown in HRTEM images (Figure 2c). Moreover, the EDS pattern of Ag-CoFe$_2$O$_4$/rGO indicates the presence of Ag, Co, Fe, and O elements (Figure 2d) in the nanocomposite. We observed the EDS patterns at various positions to ensure a uniform distribution of the elements and reached similar results. These observations ensure the dispersion of Ag-CoFe$_2$O$_4$ onto the surface of the rGO nanosheets."

The chemical states and surface composition of the Ag-

"CoFe$_2$O$_4$/rGO nanocomposite were confirmed by the XPS analysis. In Figure 3a, the XPS spectrum of Co 2p depicted two main peaks at ~780.3 and ~795.7 eV, which corresponds to Co 2p$_{3/2}$ and Co 2p$_{1/2}$, respectively. Similarly, the spectrum of Fe 2p exhibits two peaks located at around 710.9 and 726.3 eV (Figure 3b), which are assigned to Fe 2p$_{3/2}$ and Fe 2p$_{1/2}$, respectively, which, in turn, signify a +3 valence state of Fe ions. The XPS spectrum of Ag 3d in Figure 3c shows two characteristic peaks at binding energies ~368.6 and 374.9 eV that belong to Ag$^+$ 3d$_{5/2}$ and Ag$^+$ 3d$_{3/2}$, respectively. Moreover, Figure 3d shows the XPS spectra of C 1s peaks at 285.1 and 287.92 eV. The corresponding O 1s spectrum is shown in Figure 3e, and the peaks at 530.04 and 532.02 eV are attributed to the lattice oxygen in the spinel materials. Hence, this study approves the formation of the Ag-CoFe$_2$O$_4$/rGO nanocomposite.

To investigate the effect of rGO on the microstructural properties of the CoFe$_2$O$_4$ nanoparticles, the FTIR spectra were registered in the wavenumber range of 400–4000 cm$^{-1}$. The FTIR spectra of pure CoFe$_2$O$_4$ nanoparticles, Ag-CoFe$_2$O$_4$, and Ag-CoFe$_2$O$_4$/rGO nanocomposites are presented in Figure 4. The prominent band presented at about 592 cm$^{-1}$ corresponds to the stretching vibration of Fe(Co)–O. The O–H stretching vibrations interacting through H bonds are observed at ~3435, 2923, and 3446 cm$^{-1}$, and the absorption band present at ~1634 cm$^{-1}$ is due to the bending of the absorbed water molecules. These results reveal the formation of the single-phase spinal structure of CoFe$_2$O$_4$ as also confirmed by the XRD analysis.

**Optical Properties.** UV–vis absorption spectroscopy was utilized to examine the optical properties of CoFe$_2$O$_4$, Ag-CoFe$_2$O$_4$, and Ag-CoFe$_2$O$_4$/rGO nanocomposites, and the spectra are displayed in Figure 5a. It is clearly evident that the absorption edge gradually shifts toward the higher wavelength for the nanocomposites as compared to the pure CoFe$_2$O$_4$ nanoparticles. A change in the optical absorption edge indicates a variation in the energy gap of the samples and hence the band gap ($E_g$) can be determined using the Tauc relation given by

$$
α = K\frac{(hν - E_g)^n}{hν}
$$

where $K$ is a constant, $α$ is the absorption coefficient, and $hν$ is the photon energy. Moreover, the value of $n$ describes the type of transition in a semiconductor. The energy gap of the samples is evaluated from the plot between $(ahν)^2$ and $hν$ as shown in Figure 5b. It is noticed that CoFe$_2$O$_4$ has a direct band gap with a value of 1.82 eV and well-matched with earlier reports. However, by the loading of Ag nanoparticles, i.e., for Ag-CoFe$_2$O$_4$ a red shift is noticed in the band edge that may be associated with the decrease in the band gap value to 1.74 eV. Similarly, after the incorporation of 2 wt % rGO (e.g., Ag-CoFe$_2$O$_4$/rGO nanocomposite), the energy gap further reduced to 1.63 eV, which is smaller as compared to the other two samples. The red shift may be ascribed to the accessional sub-band gap energy by the serious interface and surface defects formation in the nanoparticles. These results

Table 1. Structural, Optical, and Magnetic Parameters of CoFe$_2$O$_4$, Ag-CoFe$_2$O$_4$, and Ag-CoFe$_2$O$_4$/rGO Samples

| composition          | particle size (nm) (TEM) | crystallite size (nm) (XRD) | band gap (eV) | $H_s$ (kOe) | $M_r$ (emu/g) $\times 10^{-2}$ | $M_{sat}$ (emu/g) $\times 10^{-2}$ |
|----------------------|-------------------------|-----------------------------|---------------|-------------|-------------------------------|-------------------------------|
| CoFe$_2$O$_4$        | 35 ± 1.5                | 32 ± 1.9                    | 1.82          | 1.43        | 28.9                          | 68.5                          |
| Ag-CoFe$_2$O$_4$     | 40 ± 1.3                | 38 ± 1.6                    | 1.74          | 1.42        | 22.9                          | 54.5                          |
| Ag-CoFe$_2$O$_4$/rGO | 46 ± 1.2                | 44 ± 1.3                    | 1.63          | 1.47        | 20.1                          | 48.3                          |
Figure 2. (a, b) TEM images of bare CoFe$_2$O$_4$ and Ag-CoFe$_2$O$_4$/rGO. (c, d) HRTEM image and EDS spectrum of the Ag-CoFe$_2$O$_4$/rGO nanocomposite.

Figure 3. XPS analysis of the synthesized Ag-CoFe$_2$O$_4$/rGO nanocomposite for different core level spectra: (a) Co 2p, (b) Fe 2p, (c) Ag 3d, (d) C 1s, and (e) O 1s.
divulge that the incorporation of graphene in the Ag nanocomposite can reduce the electron−hole recombination rate, which can improve the photocatalytic activity of the Ag-CoFe2O4/rGO nanocomposite.

**Photoluminescence Studies.** Room-temperature PL measurements were carried out to study the electron−hole recombination rate of the samples under 340 nm excitation and are presented in Figure 6. It is evident that the spectrum of the CoFe2O4 nanoparticles exhibits a peak at 390 nm, which may have originated due to the recombination of holes and electrons in the valence and conduction bands.42 A similar PL spectrum is also obtained for the Ag-CoFe2O4 and Ag-CoFe2O4/rGO nanocomposites; however, the intensity of the peak is lesser than that of CoFe2O4. Moreover, the Ag-CoFe2O4/rGO sample exhibits a smaller emission peak intensity in comparison with that of Ag-CoFe2O4, which further signifies the effective separation of the photogenerated charge carriers leading to the dominance of the recombination of the photogenerated electron−hole pairs,43,44 which is highly favorable for the enhancement of photocatalytic performance.

**Photocatalytic Activity.** The synthesized samples of CoFe2O4, Ag-CoFe2O4, and Ag-CoFe2O4/rGO were also examined for their photocatalytic performance for the degradation of MB dye under visible-light irradiation. Figure 7a−c shows the absorption spectra of the aqueous solution of the dye exposed at different time intervals for different samples used as catalysts. It exhibits a gradual reduction in the intensity of a typical absorption peak at 664 nm of MB by the increase in exposure time and then almost disappeared after 100 min. It is known that the self-decomposition of the MB dye is very low under visible-light irradiation, hence it referred to as blank (without catalyst). The photo-decolorization rate of the dye is calculated by the given relation

\[
\text{decolorization efficiency(\%) } = \frac{C_0 - C}{C_0} \times 100\%
\]

where \(C_0\) and \(C\) are the initial concentration and the concentration after a particular irradiation time for MB dye, respectively. Figure 7a−c displays the change in the intensity of the characteristic absorption peak of the dye as a function of irradiation time. After light irradiation for 100 min, the intensity of the absorption peak at 664 nm almost vanishes in the CoFe2O4, Ag-CoFe2O4, and Ag-CoFe2O4/rGO samples, and their degradation efficiency is estimated to be 78.03, 83.04, and 93.25%, respectively (Figure 7d). The substantial improvement in the degradation efficiency of Ag-CoFe2O4/rGO as a catalyst may be attributed to the incorporation of rGO in the nanocomposite and the electron−hole pairs could be efficiently separated for the high electron transfer capability of the CoFe2O4 nanoparticles.45 Additionally, graphene in Ag-CoFe2O4 can promote the separation efficiency of the electron−hole pairs that result in the higher photocatalytic activity of the Ag-CoFe2O4/rGO nanocomposite.

**Reusability and Stability of Ag-CoFe2O4/rGO Nanocomposite.** To meet the potential applications of the catalysts, reusability and stability examination of the as-prepared samples could be considered as important factors. The stability and recyclability of the Ag-CoFe2O4/rGO nanocomposite are examined throughout five repeated runs under constant experimental conditions, and the outcomes are displayed in Figure 8. It exhibits only a 5% reduction in the degradation efficiency after five cycles, which reveals that the photocatalyst is highly stable during the degradation of the MB
dye. These results suggest that the nanocomposite Ag-CoFe$_2$O$_4$/rGO has excellent stability and great practical application value.

**Specific Surface Area and BET Analysis.** To investigate the specific surface area of the CoFe$_2$O$_4$ nanoparticles and the Ag-CoFe$_2$O$_4$/rGO nanocomposite, Brunauer–Emmett–Teller (BET) gas sorption measurements were performed. The BET isotherms of the samples in Figure 9a,b present type IV adsorption as per the IUPAC classification and reveal the mesoporous structure of the samples. The specific surface area of the pure CoFe$_2$O$_4$ nanoparticles calculated by the isotherm is about 28.51 m$^2$/g, while it is found to be 38.60 m$^2$/g in the case of the Ag-CoFe$_2$O$_4$/rGO nanocomposite, which is much higher as compared to that of the CoFe$_2$O$_4$ nanoparticles. The higher BET surface area of the Ag-CoFe$_2$O$_4$/rGO nanocomposite indicates that the silver-decorated cobalt ferrite nanoparticles are uniformly distributed on the rGO matrix, and the materials possess a large surface area, which may result in its superior photocatalytic activity.

**Magnetic Properties.** Magnetization as a function of the applied magnetic field ($M$–$H$) was measured for CoFe$_2$O$_4$, Ag-CoFe$_2$O$_4$, and Ag-CoFe$_2$O$_4$/rGO samples at room temperature and is presented in Figure 10. It reveals the typical ferromagnetic behavior of all of the prepared samples, and the estimated values of coercivity ($H_c$), remanent magnet-
Magnetization ($M_r$) and saturation magnetization ($M_s$) are given in Table 1 for all of the samples. The observed value of $M_s$ for the Ag-CoFe$_2$O$_4$/rGO nanocomposite is found to be 48.3 emu/g, which is significantly lower than its theoretical value (i.e., $M_s \sim 80$ emu/g) for the bulk composite at room temperature. The tunable magnetic properties of the CoFe$_2$O$_4$ nanoparticles could be ascribed to the modification of the surface morphology and particle size. Conversely, reduction in the saturation magnetization in the case of both nanocomposites may be related to the decrease in the spin polarization of Fe$_{3d}$ states and the existence of nonmagnetic properties of graphene sheets. These results can be elucidated on the basis of higher surface area available in the case of nanocomposite samples.

Electrochemical Performance. The electrochemical performance of the CoFe$_2$O$_4$, Ag-CoFe$_2$O$_4$, and Ag-CoFe$_2$O$_4$/rGO nanocomposites was analyzed by employing the cyclic voltammetry (CV) measurements. The typical CV curves for CoFe$_2$O$_4$ at different scanning rates from 15 to 150 mV/s are presented in Figure 11a. The electrochemical measurements are performed with a conventional three-electrode system in 1 M KOH electrolyte solution. It is observed that the area of CV curves increases with the increase of the scan rates, which signifies the pseudocapacitive nature of the electrode. The pseudocapacitive mechanism of the samples may depend on the electrochemical adsorption–desorption reaction at the interface between electrode and electrolyte. It is also evident that the peaks became broader with the increase in scanning rate, suggesting an increase in electrode resistance. In addition, Figure 11b clearly exhibits two distinct peaks that are ascribed to the oxidation and reduction reactions, which are indicative of the redox charge storage behavior. It is obvious that both the oxidative and the reduction peaks in Ag-CoFe$_2$O$_4$/rGO are higher than those of the other samples (Figure 11c). The relation between the peak current ($i_p$) and the CV scan rate ($v$) is given by

$$i_p = 2.69 \times 10^5 n^{3/2} A D^{1/2} c^{1/2} v^{1/2}$$

(2)

where $n$, $A$, $D$, and $c$ are the number of electrons involved in the reduction, the area of the electrode ($cm^2$), the diffusion coefficient of the substrate, and the concentration of the substrate, respectively.

The diffusion coefficient can be calculated through eq 2 and is found to be $9.68 \times 10^{-13}$ cm$^2$/s and $2.57 \times 10^{-12}$ cm$^2$/s for the Ag-CoFe$_2$O$_4$ and Ag-CoFe$_2$O$_4$/rGO nanocomposites, respectively. The improvement in the diffusion coefficient of Li$^+$ ions is found to be higher for Ag-CoFe$_2$O$_4$/rGO among all other samples, which may be attributed to the interfacial interactions among the cobalt ferrite nanoparticles and reduced graphene oxide, which play a vital role in the improvement of the electrochemical performance.
CONCLUSIONS

We have prepared CoFe$_2$O$_4$ nanoparticles and Ag-CoFe$_2$O$_4$ and Ag-CoFe$_2$O$_4$/rGO nanocomposites via a simple hydrothermal process. The X-ray diffraction patterns confirm the cubic spinel crystal structure in the single phase of ferrites with an average crystallite size of 32 nm. TEM images show that the nanoparticles of CoFe$_2$O$_4$ and Ag are spherical and uniformly decorated over the graphene sheets. The particle shape is almost spherical with an average size of ~35 nm. The presence of two characteristic absorption bands in the FTIR spectra confirms the formation of the single-phase CoFe$_2$O$_4$. The room-temperature magnetic hysteresis loops ensure the ferromagnetic nature of all of the samples and a systematic variation in the magnetic parameters. The results of the photocatalytic performance reveal the higher catalytic degradation of the MB dye by the Ag-CoFe$_2$O$_4$/rGO nanocomposite under visible light irradiation than that of the other studied samples, which suggests that rGO plays a key role in Ag-CoFe$_2$O$_4$ for the decomposition of the dye. An improvement in the photocatalytic performance is observed for the Ag-CoFe$_2$O$_4$/rGO nanocomposite due to highly conductive nature and the relatively higher surface area. Hence, prepared rGO-based nanocomposite could be one of the promising candidates for wastewater treatment and electrochemical applications.

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Notes
The authors declare no competing financial interest.

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