A study on the preparation and performance of a graphene-supported, Ce ion-doped, high-efficiency, magnetic TiO$_2$ photocatalyst

Weiyan Cao, Xijun Liu, Yuwei Wang, Yong Zhang and Congzhi Fu

Abstract

The preparation of a magnetic core-shell Z-scheme heterojunction Fe$_3$O$_4$@SiO$_2$@TiO$_2$-Ce/rGO composite material by sol–gel and hydrothermal methods is described. The catalytic activity of the composite photocatalyst doped with metal Ce and loaded with graphene is significantly improved. Under standard experimental conditions ($p$H = 7, [methylene blue] = 10 mg L$^{-1}$, magnetic composite photocatalyst concentration = 0.1 g 50 mL$^{-1}$), the Fe$_3$O$_4$@SiO$_2$@TiO$_2$-Ce/rGO composite photocatalyst lead to a maximum degradation of methylene blue of 98.2% in 120 min.

Keywords
cerium, graphene oxide, magnetic, photocatalysis, titanium dioxide

Date received: 18 September 2021; accepted: 21 December 2021

Introduction

With the continuous advancement of the industrial revolution, the problem of water pollution has become increasingly serious. Polluted water sources seriously endanger human health, and it is extremely important to solve the problem of water pollution.1 There are many types of pollutants in water sources, such as organic pollutants, inorganic pollutants, toxic metal ions, and harmful nitrogen oxide. Traditional sewage treatment methods are low in efficiency, high in cost, and unselective towards different pollutants. In particular, there are secondary pollution problems. Therefore, sewage treatment has not been well solved.2 As early as 1972, Fujishima and Honda discovered that TiO$_2$ in photocells could participate in a redox process with water to release clean energy ($H_2/O_2$) when exposed to light.3 In 1976, Carey and coworkers4 used TiO$_2$ semiconductors to degrade organic pollutants. Since then, photocatalytic oxidation has entered a stage of rapid development as a new water treatment technology.

TiO$_2$ as a photocatalyst has the characteristics of good stability, low cost, strong catalytic activity, and is not harmful to the environment. The photocatalytic efficiency of...
nano titanium dioxide is related to the crystal phase, particle size, and specific surface area. It has been demonstrated that anatase is the most stable and effective polymorph on a nanoscale due to its relatively low surface energy.\textsuperscript{5–7} However, due to the large band gap of TiO\textsubscript{2}, the high recombination rate of photogenerated carriers, and difficult to recycle characteristics, the application of TiO\textsubscript{2} in water treatment is limited. At present, a small amount of doping of TiO\textsubscript{2} with transition-metal lanthanide series and actinide series metals can reduce the band gap width of TiO\textsubscript{2}, and also make it photo-responsive in the visible light region, thereby improving the utilization of sunlight.\textsuperscript{8} Studies on doping of transition metals, including Ce, Co, Ni, and so on, have been reported, which show the modification effect of Ce is better compared to those of other transition metals.\textsuperscript{9–13} In addition, the main disadvantage of TiO\textsubscript{2} as a photocatalyst is that it is difficult to completely recover from wastewater. At present, several research groups have developed TiO\textsubscript{2}-based magnetic catalysts that can be quickly separated from wastewater.\textsuperscript{14,15} However, the magnetic core can reduce the photocatalytic efficiency.\textsuperscript{16} In fact, SiO\textsubscript{2}, as a magnetic isolation material, can be used as a protective film to avoid interactions between the magnetic core and the TiO\textsubscript{2} coating.\textsuperscript{17–19} Meanwhile, graphene is a two-dimensional nanomaterial with high specific surface area and high conductivity.\textsuperscript{20,21} It can improve the migration efficiency of photogenerated carriers, and therefore, the recombination of photogenerated carriers can be effectively suppressed.

In this research, a Z-scheme heterojunction Fe\textsubscript{3}O\textsubscript{4}@SiO\textsubscript{2}@TiO\textsubscript{2}-Ce/rGO core-shell material has been prepared by sol–gel and hydrothermal methods. TiO\textsubscript{2} doped with the rare earth metal Ce is loaded on graphene oxide to improve the photocatalytic activity. CeO\textsubscript{2} acts as an electron receiver to reduce electron-hole recombination, while graphene has good electrical conductivity and a large specific surface area. It can increase the contact area between pollutants and the catalyst and improve the catalytic activity of the catalyst. The principle is shown in Figure 1.

**Results and discussion**

**X-ray diffraction analysis**

As shown in Figure 2(a), characteristic diffraction peaks appear at 30.0, 35.3, 43.0, 53.5, 56.9 and 62.8, corresponding to the (220), (311), (400), (422), (511) and (440) crystal planes (JCPDS No. 26 -1136), which are the characteristic diffraction peaks of Fe\textsubscript{3}O\textsubscript{4}. Comparing Figure 2(a) and (b), it is not difficult to see that there is no obvious change between Fe\textsubscript{3}O\textsubscript{4} and Fe\textsubscript{3}O\textsubscript{4}@SiO\textsubscript{2}. This may be because the SiO\textsubscript{2} coating is amorphous; hence, no new diffraction peak occurs. Figure 2(c) and (d) shows that Fe\textsubscript{3}O\textsubscript{4}@SiO\textsubscript{2}@TiO\textsubscript{2}-Ce and Fe\textsubscript{3}O\textsubscript{4}@SiO\textsubscript{2}@TiO\textsubscript{2}-Ce/rGO have similar characteristic peaks. In addition to the established diffraction peaks of Fe\textsubscript{3}O\textsubscript{4}, new diffraction peaks appeared at 25.8, 37.8, 48.0, 53.8, 55.0, 62.1, 68.8, 70.3 and 75.0, corresponding to the (101), (004), (200), (105), (211), (213), (116), (220) and (215) crystal planes (JCPDS No. 21-1272). This shows that the introduced TiO\textsubscript{2} is mainly in the anatase phase. As shown in Figure 2(c) and (d), characteristic diffraction peaks of rGO and Ce were not observed. This may be because the amount of Ce and GO is too small and detection is not obvious.

**Scanning electron microscope image analysis**

The typical lamellar structure of GO can be clearly seen in Figure 3(a), and Figure 3(b) shows that the Fe\textsubscript{3}O\textsubscript{4} particles have a tetragonal structure. The particle size is about 400 nm and the particles are evenly distributed. Figure 3(c) clearly shows that the Fe\textsubscript{3}O\textsubscript{4} surface becomes smooth, while the edges and corners are no longer clear; at the same time the particle size has increased, indicating that SiO\textsubscript{2} has successfully coated the surface of Fe\textsubscript{3}O\textsubscript{4}. Figure 3(d) shows that on addition of Ce, the surface becomes rough and granular. The EDS spectrum shows that the Ce content is 3%, indicating that Ce metal has been successfully doped on the
surface of the TiO₂. Figure 3(e) shows that Fe₃O₄@SiO₂@TiO₂-Ce has been successfully loaded onto rGO.

**X-ray photoelectron spectroscopy analysis**

In order to determine the chemical composition, the sample was analysed by X-ray photoelectron spectroscopy (XPS). It can be clearly seen from Figure 4 that the sample is composed of Fe, Si, Ti, Ce, C and O. This proves that Ce has been successfully doped on the photocatalyst. Compared with the Ti₂p peak, the Fe₂p peak is very weak, indicating that the Fe₃O₄ core is almost completely covered by SiO₂, forming a core-shell structure. The Ce3d spectrum is shown in Figure 4(b) and (c). The V′, V″ and V‴ peaks correspond to Ce³⁺ 3d₅/₂ and Ce³⁺ 3d₃/₂; u, u′, u″ and u‴ correspond to Ce⁴⁺ 3d₃/₂, Ce⁴⁺ 3d₅/₂, Ce⁴⁺ 3d₃/₂ and Ce⁴⁺ 3d₅/₂ (V and u are used to refer to the different positions of the peaks of Ce). The CeO₂ peak shifts, which may be caused by the energy transfer after CeO₂ and TiO₂, form a heterojunction. Figure 4(f) shows the VB-XPS plots of CeO₂ and TiO₂.
can be estimated that the VB positions of CeO$_2$ and TiO$_2$ are 2.22 eV and 2.64 eV, respectively (see Figure S1 in the Supplementary Material). Fourier transform infrared (FTIR) spectroscopy analysis was used to study the bonding interactions in the fabricated Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce and Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO photocatalysts. The wide band at 3419 cm$^{-1}$ is attributed to the tensile vibration of surface water, the hydroxy (OH) group. The characteristic peak of Si–O–Si corresponds to the antisymmetric stretching vibration at 1080 cm$^{-1}$, while the Fe–O characteristic peak is at 573 cm$^{-1}$ (an asymmetric stretching vibration). Absorptions due to Ti–O–Ti, Ti–O–Si and C=C occur at 478 cm$^{-1}$ (a stretching vibration), 807 cm$^{-1}$ (a symmetrical stretch) and 1623 cm$^{-1}$ (double bond stretching vibration). The two plots do not change significantly and there is an obvious C–O–C impurity at 1226 cm$^{-1}$ in Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce. On the addition of graphene, the peak due to C=C in Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO is more obvious.

Transmission electron microscopy image analysis

In order to further clarify the morphology of the sample, we performed transmission electron microscopy (TEM) image analysis on Fe$_3$O$_4$, Fe$_3$O$_4$@SiO$_2$, Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce and Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO. Figure 5(a) shows the tetragonal configuration of Fe$_3$O$_4$ more clearly, while Figure 5(b) shows that a translucent region is formed on the surface of Fe$_3$O$_4$, indicating that Fe$_3$O$_4$ and SiO$_2$ form a core-shell structure. Figure 5(c) shows that there are many obvious particles on the outer surface of the material. According to the scanning electron microscope (SEM) and EDS results, the obvious particulate matter may be Ce, which proves that it has been successfully doped on the surface of Fe$_3$O$_4$@SiO$_2$@TiO$_2$. Figure 5(d) shows that Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce is tightly supported on the surface of rGO, confirming the successful preparation of the Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO composite material.

UV–Vis spectroscopy analysis

It can be seen from the UV–Vis diffuse reflectance spectrum of the catalyst (Figure 6) that pure TiO$_2$ samples have strong absorption in the ultraviolet region, but there is almost no absorption in the visible light region; CeO$_2$ also absorbs in the ultraviolet region but, again, almost no absorption occurs in the visible region. The absorption intensity of the photocatalyst doped with Ce is significantly enhanced under visible light and exhibits a red shift of the absorbing boundary. This shows that Ce doping can expand the response range of TiO$_2$ in the visible light region. The photocatalyst loaded with rGO further improves the absorption performance of the catalyst under visible light. Figure 6(b) is the Tauc graph driven by the UV-DRS spectrum. It can be estimated that the energy band gaps of Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO, Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce, TiO$_2$ and CeO$_2$ are 2.07 eV, 2.05 eV, 3.20 eV and 2.71 eV, respectively. The band gap of Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO is narrowed, which further proves that the addition of CeO$_2$ can significantly improve the photocatalytic efficiency of TiO$_2$. The adsorption performance of the photocatalyst is characterized by an N$_2$ physical adsorption experiment, and the corresponding N$_2$ adsorption-desorption isotherm is shown in Figure S2 (see the Supplementary Material). It can be seen that the Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce and Fe$_3$O$_4$@SiO$_2$@TiO$_2$–Ce/rGO samples show the shape of a type IV isothermal curve and that they are mesoporous structures. Electron microscopy showed that the particle size was about 40 nm. This was confirmed by previous electron microscopy. These studies showed that the
specific surface areas of Fe₃O₄, Fe₃O₄@SiO₂@TiO₂-Ce and Fe₃O₄@SiO₂@TiO₂-Ce/rGO were 3.7660, 40.6405 and 46.9017 m² g⁻¹, respectively. The increase in specific surface area is conducive to the adsorption of pollutants and the promotion of photocatalytic degradation of pollutants.

Electrochemical impedance spectroscopy analysis

Electrochemical impedance spectroscopy is a method used to characterize charge transfer. The smaller the curve radius, the smaller the resistance. The Nyquist curve in Figure 7 exhibits the largest radius for TiO₂, the second is Fe₃O₄@SiO₂@TiO₂-Ce, and the smallest is for the Fe₃O₄@SiO₂@TiO₂-Ce/rGO composite material. This shows that the Fe₃O₄@SiO₂@TiO₂-Ce/rGO composite material has the highest charge transfer efficiency. This is due to the large π-bond structure of the loaded graphene, which promotes photogenerated electron transfer. Graphene is also an excellent electron acceptor, thereby reducing recombination with holes. This is consistent with the UV test.

Photoluminescence analysis

The recombination of photogenerated carriers reduces the activity of the TiO₂ photocatalyst. Therefore, photoluminescence (PL) analysis is used to measure the luminescence intensity of the fluorescence generated by the recombination of photogenerated carriers. Figure 8 clearly shows that the fluorescence intensities of pure TiO₂, Fe₃O₄@SiO₂@TiO₂-Ce and Fe₃O₄@SiO₂@TiO₂-Ce/rGO gradually decrease. It also shows that doping Ce and loading rGO reduces the recombination efficiency of photogenerated carriers. This is consistent with the EIS results. Therefore, the photocatalytic activity is improved.

Photocatalytic activity and magnetic test

As shown in Figure 9(a), the photocatalytic activity of the sample was studied via the photodegradation rate of methylene blue (MB) under visible light irradiation. The absorbance of MB after degradation was measured with an UV–Vis near-infrared spectrophotometer. The degradation efficiency of the photocatalyst increases with time. The
The photocatalytic activity of Fe₃O₄@SiO₂ is 0, while the photocatalytic activity of TiO₂ is very low, and the degradation rate is 8.7%. The photocatalytic activity of the Fe₃O₄@SiO₂@TiO₂-Ce composite material obtained after metal Ce doping improves greatly and the degradation rate is 75.4%. That of the Fe₃O₄@SiO₂@TiO₂-Ce/rGO composite material is 98.2%. This shows that the supported graphene plays a significant role in improving the photocatalytic activity of the photocatalyst. This is because the excitation TiO₂ conduction band electrons can be transferred to the graphene sheet which prevents photogenerated electrons from recombining with holes. This is consistent with the PL test results. The UV–Vis DRS also proved that the band gap width of the modified TiO₂ photocatalyst was reduced and the visible light absorption region was greatly improved. The EIS test results are consistent with the UV–Vis DRS and PL tests. Therefore, the photocatalytic activity is improved. The samples prepared in this experiment have high degradation efficiency over relatively short times.

### Comparison of the degradation performances

Table 1 shows a comparison of the degradation efficiency of the photocatalytic materials and other similar materials in this experiment (the degradation rates are those under the optimal degradation conditions). The samples prepared in this experiment have high degradation efficiency over relatively short times.

#### Table 1. Comparison of the photocatalytic degradation rates of similar materials.

| Sample                        | Magnetic | Targeted contaminant | Degradation time | Rate  | Ref.     |
|-------------------------------|----------|----------------------|-------------------|-------|----------|
| Fe₃O₄@TiO₂-Ce/rGO             | Yes      | Methylene blue       | 120 min           | 98.2% | This work|
| Ag@Fe₃O₄@C-Au@TiO₂            | Yes      | Methylene blue       | 360 min           | 97.0% | Shen et al.¹³ |
| Fe₃O₄@SiO₂@TiO₂               | Yes      | Rhodamine B          | 180 min           | 95%   | Ma et al.¹⁵ |
| TiO₂/MMT/Fe₃O₄                | Yes      | Methylene blue       | 80 min            | 94%   | Zhang et al.²⁹ |
| γ-Fe₂O₃@SiO₂@TiO₂-Ag          | Yes      | Basic blue 41        | 3 h               | 94%   | Dabirvaziri et al.¹⁸ |
| Ag₂O/TiO₂ NTA                 | No       | Methylene blue       | 120 min           | 93.89%| Hou et al.¹⁰ |

### Mechanistic analysis

According to the above analysis, the catalytic degradation principle of the Fe₃O₄@SiO₂@TiO₂@Ce/rGO nanocomposite can be deduced (Figure 10). Under visible light irradiation, the electrons on the valence band of TiO₂ and CeO₂ are excited by the light and transition to the conduction band. Due to the band structure of the two materials, the photogenerated electrons excited to the conduction band of TiO₂ recombine with the photogenerated holes on CeO₂, and as a result, a large number of holes are generated in the TiO₂ valence band, along with a large number of electrons...
in the CeO	extsubscript{2} conduction band; the two materials form a Z-type heterostructure.

**Conclusion**

In this experiment, a Z-scheme heterojunction magnetic composite material, Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}-Ce/rGO, was prepared by the sol-gel and hydrothermal methods. The morphology and structure are characterized by TEM, SEM, X-ray diffraction (XRD) and FTIR, and performance tests via UV–Vis DRS, PL, N	extsubscript{2} gas adsorption, EIS and so on. All proved that the prepared Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}-Ce/rGO composite material has high catalytic activity. SiO	extsubscript{2} plays a protective role, isolates Fe	extsubscript{3}O	extsubscript{4} and TiO	extsubscript{2}, and prevents the performance of TiO	extsubscript{2} from being diminished. The cerium and Ti metals undergo charge transfer and form a Z-type heterojunction structure. The supported reduced graphene oxide increases the specific surface area of the composite material and enhances the electrical conductivity. The prepared high-efficiency magnetic recyclable composite material has broad application prospects in the treatment of factory wastewater.

**Experimental**

**Materials and equipment**

Fe	extsubscript{3}O	extsubscript{4} was obtained from Luoyang Haorun Information Technology Co. Ltd. Graphene Oxide was purchased from Shenzhen Tuling Evolution Technology Co. Ltd. Ethyl orthosilicate (TEOS), tetrabutyl titanate (TBOT), MB, sodium dodecylbenzene sulfonate (SDBS), HNO	extsubscript{3}, glacial acetic acid, Ce(NO	extsubscript{3})	extsubscript{3}·6H	extsubscript{2}O and C	extsubscript{2}H	extsubscript{5}OH were obtained from Shenzhen Tuling Evolution Technology Co. Ltd. and the other reagents are of analytical grade and were used without further purification.

A D8 Advance X-ray diffractometer (Bruker-AXE, Germany), S-3400 scanning electron microscope (Hitachi, Japan), Lambda750 UV–Vis-NIR spectrophotometer (PE, USA), a CEL-LAB500 series of multi-position photochemical reactions instrument (photolysis instrument) (Beijing Zhongjiao Jinyuan Technology Co., Ltd.), a UV-5100B UV–Vis spectrophotometer (Shanghai Analytical Instrument Co., Ltd.) and an FLS920 transient steady-state fluorescence spectrophotometer (Edinburgh, UK) were employed.

**Synthesis of Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2} nanoparticles**

Fe	extsubscript{3}O	extsubscript{4} (0.3 g) was weighed in a 100 mL beaker and diluted HCl (50 mL, 0.1 mol L	extsuperscript{-1}) was added. The mixture was subjected to sonication for 15 min. Next, the Fe	extsubscript{3}O	extsubscript{4} solid was magnetically separated and washed three times with deionized water. The magnetically separated Fe	extsubscript{3}O	extsubscript{4} solid was placed in a 250 mL three-necked flask, and deionized water (18 mL) and absolute ethanol (80 mL) were added. Then, after stirring for 30 min at room temperature, NH	extsubscript{4}H	extsubscript{2}O was added. After stirring for 30 min, TEOS was added slowly (0.6 mL) and the stirring was continued for 12 h. The product, Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}, was separated magnetically and was washed and dried. The product was then dried at 60°C for 12 h.

Ce(NO	extsubscript{3})	extsubscript{3} is calcined at high temperature to generate CeO	extsubscript{2}. CeO	extsubscript{2}(NO	extsubscript{3})	extsubscript{2} (0.1 g) was weighed in a 100 mL beaker and 

H	extsubscript{2}O (1.8 mL), HNO	extsubscript{3} (0.2 mL) and absolute ethanol (20 mL) were added to make solution A. Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2} (0.2 g) was weighed in a 100 mL beaker and absolute ethanol (20 mL) and acetic acid (0.25 mL) were added. The mixture was subjected to sonication for 40 min, tetrabutyl titanate (5 mL) was added, and the mixture was then mechanically stirred in a 35°C water bath for 30 min to prepare liquid B. Solution A was slowly added to liquid B through a peristaltic pump, the mixture was stirred evenly until a sol was formed, and aged at 30°C for 18 h. The obtained gel was dried in an oven at 80°C for 24 h, and the dried gel was ground and calcined under a nitrogen atmosphere at 450°C for 2 h to obtain Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}@Ce powder.

**Synthesis of Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}-Ce/rGO nanoparticles**

Graphene oxide (0.08 g) was weighed in a 100 mL beaker and absolute ethanol (40 mL) and deionized water (20 mL) were added successively. The mixture was subjected to sonication for 1 h, and SDBS (0.15 g) and Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}@Ce (0.2 g) powder were added 10 min later followed by further sonication for 1 h. The reaction solution was transferred to a 100 mL high-pressure reactor and placed in a 120°C oven to continue the reaction for 3 h. After the high-pressure reactor had cooled, the product was magnetically separated, and washed three times with absolute ethanol and deionized water. The product was dried at 60°C for 24 h (Oxidation of graphene to graphene oxide).

**Performance test on Fe	extsubscript{3}O	extsubscript{4}@SiO	extsubscript{2}@TiO	extsubscript{2}-Ce/rGO**

Using visible light as the light source, the photocatalytic performance of the photocatalyst was evaluated by assessing the photodegradation rate of MB. The magnetic photocatalyst (0.1 g) was dispersed in a MB solution (50 mL, 10 mg L	extsuperscript{-1}), and testing was performed in a multi-position photochemical reactor (the light source was a 300 W xenon lamp). The suspension was stirred for 20 min in the light before changing to dark to establish the MB adsorption equilibrium. A 5 mL aliquot of the supernatant was removed after exposure to light every 10 min and analysed with detection with a spectrophotometer after centrifugation. The degradation rate was used to measure the degree of degradation of MB.

**Acknowledgements**

The authors acknowledge Qiqihaer University for analysis and the testing centre for assistance with the measurements.

**Author contributions**

L.X. and Y.W. guided the experiments, the test processes and revised the paper. W.C. designed and conducted the experiments and wrote the manuscript. Y.Z. performed the testing. C.F.
analysed the data. All authors discussed the results and commented on the manuscript.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding
The author(s) received no financial support for the research, authorship and/or publication of this article.

ORCID iD
Weiyan Cao https://orcid.org/0000-0001-6187-8296

Supplemental material
Supplemental material for this article is available online.

References
1. Yuan J, Lu Y, Wang C, et al. Ecosyst Health Sust 2020; 6: 1–17.
2. Prasad B, Ghosh C, Chakraborty A, et al. Desalination 2011; 274: 105–112.
3. Fujishima A and Honda K. Nature 1972; 238: 37–38.
4. Tosine HM, Lawrence J and Carey JH. Bullet Environ Contam Toxicol 1976; 16: 697–701.
5. Han F, Zhu L, Huang Z, et al. J Phys Chem Lett 2020; 11: 7590–7594.
6. Cho YS, Lee Y, Park JKJ, et al. J Nanosci Nanotechnol 2020; 20: 6738–6746.
7. Li YY, Wang JG, Liu XR, et al. ACS Appl Mater Interf 2017; 9: 31691–31698.
8. Fu C, Liu X and Wang X. New J Chem 2020; 44: 5755–5761.
9. Rostami M. J Mol Struct 2019; 1185: 191–199.
10. Hou J, Zhou J, Liu Y, et al. J Alloys Comp 2020; 849: 156493.
11. Wang D, Li Q, Miao W, et al. Chem Eng J 2020; 402: 126211.
12. Li W, Xie L, Zhou L, et al. Ceramic Int 2020; 46: 24744–24752.
13. Shen M, Chen S, Jia W, et al. J Nanopart Res 2016; 18: 356.
14. Hu QL, Wang LS, Yu NN, et al. Rare Metals 2017; 39: 1333–1340.
15. Ma J-Q, Guo SB, Guo XH, et al. J Nanopart Res 2015; 17: 307.
16. Esfandiar N, Kashefi M, Afsharnezhad S, et al. Mater Chem Phys 2020; 244: 122633.
17. Mokhtarifar M, Kaveh R, Bagherzadeh M, et al. ACS Appl Mater Interf 2020; 12: 29671–29683.
18. Dabirvaziri B, Givinrad MH, Sourinejad I, et al. J Environ Health Sci Eng 2019; 17: 949–960.
19. Liu H, Jia Z, Ji S, et al. Catal Today 2011; 175: 293–298.
20. Nien YH, Hsum HH, Hu GM, et al. IEEE T Electr Dev 2020; 67: 3660–3666.
21. Khalifeh R, Naseri V and Rajabzadeh M. Chem Select 2020; 5: 11453–11462.
22. Fiorenza R, Bellardita M, Barakat T, et al. J Photochem Photobiol A: Chem 2018; 352: 25–34.
23. Veziroglu S, Roder K, Gronenberg O, et al. Nanoscale 2019; 11: 9840–9844.
24. Kumar V, Chen WF, Zhang X, et al. Ceramic Int 2019; 45: 22085–22094.
25. Yan H, Wang R, Liu R, et al. Appl Catal B: Environ 2021; 291: 120096.
26. Natile MM, Boccaletti G and Glisenti A. Chem Mater 2005; 17: 6272–6286.
27. Hezam A, Namratha K, Drmosh QA, et al. ACS Appl Nano Mater 2019; 3: 138–148.
28. Fu C, Liu X, Wang Y, et al. RSC Adv 2019; 9: 20256–20265.
29. Zhang P, Mo Z, Han L, et al. Ind Eng Chem Res 2014; 53: 8057–8061.