Direct Synthesis of Magnetic CoFe$_2$O$_4$ Nanoparticles as Recyclable Photo-Fenton Catalysts for Removing Organic Dyes

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ABSTRACT: Herein, CoFe$_2$O$_4$ nanoparticles were directly synthesized through a solution combustion method using ferric nitrate, cobalt nitrate, and glycine as raw materials. The effects of glycine on the phase composition and magnetic properties of the CoFe$_2$O$_4$ products were investigated. When the fuel/ferric nitrate ratio was 0.8, the obtained product was pure CoFe$_2$O$_4$ with an average particle size of 25 nm. Furthermore, the saturation magnetization is 77.3 emu/g, which is about 95.7% that of CoFe$_2$O$_4$ bulk materials at room temperature and good for recycling. The photo-Fenton catalytic properties of CoFe$_2$O$_4$ were investigated for assessing its efficacy in removing dyes. It could degrade the 20 ppm MB in 75 min. To improve the photo-Fenton catalytic performance, NH$_4$HCO$_3$ and glucose were employed as additives. Due to the pores formed by NH$_4$HCO$_3$ and glucose, the G-CoFe$_2$O$_4$ and N-CoFe$_2$O$_4$ could degrade the 20 ppm MB in 40 and 25 min, respectively. The results indicated that these additives can effectively improve the catalytic activity of CoFe$_2$O$_4$. The modified CoFe$_2$O$_4$ is a promising alternative recyclable photo-Fenton catalyst for removing organic dyes.

1. INTRODUCTION

Organic dyes generated by industrial waste pose a significant threat to human health and the environment. Therefore, developing effective technologies to degrade organic dyes in wastewater is extremely important for a sustainable society.$^{1,2}$ Many technologies have been employed for organic dye degradation, including adsorption, chemical precipitation, biological processes, and advanced oxidation processes.$^{3-6}$ Photo-Fenton catalysis is an advanced oxidation process that attracted significant attention for the production of oxide species ($\cdot$OH), which are efficient oxidants with high redox potential.$^{7,8}$ In particular, photo-Fenton catalysts based on transition metal oxides (e.g., Fe, Co, and Cu) have been studied extensively because they are inexpensive, environmentally benign, magnetically recyclable, and exhibit visible light responses.$^{9-13}$ Among these metal oxides, spinel-type cobalt ferrite (CoFe$_2$O$_4$) has been intensively studied for degradation of organic dyes due to its excellent stability, separation, and catalytic activity.$^{14}$ Thus far, a variety of methods have been proposed to synthesize CoFe$_2$O$_4$ including sol–gel methods,$^{16}$ and chemical synthesis methods.$^{17}$ However, such methods typically involve complicated procedures, including long reaction duration, repeated washing, and calcination, to obtain the final products. A facile and efficient synthesis method would be important for practical applications. To prepare magnetic CoFe$_2$O$_4$ nanoparticles, we developed a solution combustion synthesis (SCS) method producing oxide nanomaterials with a high yield. This method is essentially an exothermal redox reaction between fuels and oxidizers.$^{18-20}$ In general, the oxidizers are metal nitrates and the fuels are glycine, citric acid, urea, etc.$^{21}$ Additionally, the energy generated by exothermal reactions can be used to sustain the reaction system.

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Furthermore, the apparatuses used for this process are simple and cost-effective.22 The magnetic properties of a material heavily depend on its particle size and fabrication method.23 Various undesirable phases may exist in products, weakening their magnetic properties.24 With the advantages and characteristics of SCS, it is possible to prepare pure CoFe$_2$O$_4$ nanoparticles in a single step without further processing.

We present a direct method of the preparation of pure CoFe$_2$O$_4$ nanoparticles via SCS reactions between metal nitrates and glycine. The entire synthesis process is completed in 10−15 min. The effects of glycine on the synthesis of CoFe$_2$O$_4$ nanoparticles and the magnetic properties of the obtained nanoparticles were extensively studied. The photo-Fenton catalytic and recycling performances of the synthesized CoFe$_2$O$_4$ were investigated for dye degradation. To improve photo-Fenton catalytic performance, NH$_4$HCO$_3$ and glucose were introduced as additives.

2. RESULTS AND DISCUSSION

Previously reported studies have indicated that the phase and microstructure of SCS products depend on the fuel-to-oxidant ratio ($\phi$).25 First, the XRD patterns of the prepared products with different $\phi$ values were studied. As shown in Figure 1a, the diffraction peaks closely match those of cubic spinel CoFe$_2$O$_4$. For $\phi = 0.6, 0.7,$ and $0.8$, no additional peaks can be detected for any impurity phases, and the strong diffraction peaks indicate that the CoFe$_2$O$_4$ products have good crystallinity. For $\phi = 0.9$, additional peaks were located at 32 and 61.5°, which are characteristic peaks of CoO. These XRD results confirm that the parameter $\phi$ affects the phase composition of the SCS products. This is due to the different chemical energy liberated from a different fuel-to-oxidant ratio, and then, the chemical energy transforms the metal ions to the corresponding metal oxide with a different oxidation state.

To gain a better understanding of the formation of CoFe$_2$O$_4$ ($\phi = 0.8$) during SCS, we studied the process using TG-DSC. Figure 2a presents the results. At 174 °C, there is an exothermic peak accompanied by a huge weight loss. It is noteworthy that the SCS process is a redox exothermic reaction between an oxidizer and fuel. In this reaction system, the ferric nitrate and cobalt nitrate acted as oxidizers, and the glycine acted as the fuel (reducer). Additionally, the glycine also acted as a complexing agent.26 When all the raw materials were dissolved in water, the materials were in their atomic or molecular states. The glycine complexes the Fe$^{3+}$ and Co$^{2+}$ to form a gel, as shown Figure 2b. During heating, water experienced volatilization and an exothermic reaction between the oxidizer and fuel occurred at approximately 174 °C. The reaction is described in eq 1. The huge weight loss can be attributed to the gases (CO$_2$, H$_2$O, and N$_2$) released during the SCS reaction.
$18\text{Fe(NO}_3\text{)}_3 + 9\text{Co(NO}_3\text{)}_2 + 40\text{C}_2\text{H}_5\text{NO}_2$

$\rightarrow 9\text{CoFe}_2\text{O}_4 + 80\text{CO}_2 \uparrow + 10\text{OH}_2\text{O} \uparrow + 56\text{N}_2\uparrow$  \hspace{1cm} (1)

Figure 3 presents SEM images of the CoFe$_2$O$_4$ products with different $\varphi$ values. All products exhibit a flocculent structure.

The microstructure of the product with $\varphi = 0.8$ is presented in Figure 4. It is clear that this CoFe$_2$O$_4$ product has a two-dimensional flocculent structure (Figure 4a). To obtain additional information, high-resolution TEM was conducted, as shown in Figure 4b. One can see that the product is composed of CoFe$_2$O$_4$ particles approximately 25 nm in size.

Figure 5 presents the hysteresis loops measured at room temperature for CoFe$_2$O$_4$ products with different $\varphi$ values, and all the samples exhibit typical ferromagnetic characteristics. The CoFe$_2$O$_4$ product for $\varphi = 0.8$ has the highest magnetization saturation (Ms) value of 77.3 emu/g, which is 95.7% of the value of bulk CoFe$_2$O$_4$ materials value (80.8 emu/g) at room temperature.\hspace{1cm} (27) The Ms values for $\varphi = 0.6$, 0.7, and 0.8 are 54.2, 59.5, and 29.9 emu/g, respectively. The Ms values for magnetic nanoscale materials depend heavily on their chemical composition and crystallinity.\hspace{1cm} (28) Therefore, the high saturation magnetization value with $\varphi = 0.8$ is attributed to high crystallinity and a pure CoFe$_2$O$_4$ phase. For $\varphi = 0.9$, the product is composed of both CoFe$_2$O$_4$ and CoO, resulting in the lowest saturation magnetization. For $\varphi = 0.6$, 0.7, and 0.8, the coercive field is closely based on the pure CoFe$_2$O$_4$ phase in the samples. It is noteworthy that the coercive field for the $\varphi = 0.9$ sample is twice as large as that for the other values. This indicates that CoO in samples can enhance the coercive field value. This enhancement is attributed to the reduction of interparticle interactions between CoFe$_2$O$_4$ particles.

The photo-Fenton catalytic activity of CoFe$_2$O$_4$ ($\varphi = 0.8$) was investigated based on the degradation of MB. The absorbance spectra of 100 mL of MB solutions (20 ppm) were recorded between 0 and 75 min in the presence of 5 mg of CoFe$_2$O$_4$ particles. The absorbance spectra are presented in Figure 6. The absorbance and concentration of the MB decrease gradually with increasing reaction time.

Figure 3. SEM images of CoFe$_2$O$_4$ products with different $\varphi$ values: (a) $\varphi = 0.6$, (b) 0.7, (c) 0.8, and (d) 0.9.

Figure 4. (a) TEM image and (b) high-resolution TEM image of the CoFe$_2$O$_4$ product ($\varphi = 0.8$).

Figure 5. Magnetic hysteresis loops of the CoFe$_2$O$_4$ products with different $\varphi$ values: (a) 0.6, (b) 0.7, (c) 0.8, and (d) 0.9.

Figure 6. Absorbance spectra of 100 mL solutions of MB (20 ppm) in the presence of 5 mg of CoFe$_2$O$_4$ particles.

Various studies have indicated that catalytic materials with large SSAs based on the presence of mesopores can improve chemical activity.\hspace{1cm} (29,30) Therefore, we adopted NH$_4$HCO$_3$ and glucose used as additives to form additional pores. Samples prepared with NH$_4$HCO$_3$ (4 g) and glucose (2 g) were labeled as N-CoFe$_2$O$_4$ and G-CoFe$_2$O$_4$, respectively. Because the CoFe$_2$O$_4$ particle preparation is an exothermic process, NH$_4$HCO$_3$ and glucose were decomposed during reaction. Additionally, the particles were prepared in air, meaning that the
O₂ in the air could participate in the reactions. These reactions are defined in eqs 2 and 3.

\[
\begin{align*}
4\text{NH}_4\text{HCO}_3 + 3\text{O}_2 & \rightarrow 10\text{H}_2\text{O} + 2\text{H}_2 + 4\text{CO}_2 \\
\text{C}_6\text{H}_5\text{O}_6 + 6\text{O}_2 & \rightarrow 6\text{H}_2\text{O} + 6\text{CO}_2
\end{align*}
\]

(2)

(3)

All products in reactions are in a gaseous phase. A significant amount of gases escape during the preparation process, forming mesopores in the CoFe₂O₄. Figure 7 presents the SEM micrographs of N-CoFe₂O₄ and G-CoFe₂O₄.

Based on the incorporation of additives for pore-forming, the N-CoFe₂O₄ and G-CoFe₂O₄ samples exhibit enhanced SSAs, pore diameters, and pore volumes. Additionally, the dispersant effect of gases can prevent the agglomeration of nanoparticles. The energy generated by the reactions can be removed from the reaction system by the gases, which can inhibit grain growth. TEM micrographs of N-CoFe₂O₄ and G-CoFe₂O₄ are presented in Figure 8.

The TEM micrographs of N-CoFe₂O₄ (Figure 8a) and G-CoFe₂O₄ (Figure 8c) are consistent with the SEM micrograph (Figure 8a,b). The sizes of the N-CoFe₂O₄ and G-CoFe₂O₄ particles are smaller than those of the CoFe₂O₄ samples (Figure 4b). The average sizes of the N-CoFe₂O₄ and G-CoFe₂O₄ particle are 20 and 10 nm, which are observed in Figure 8b and Figure 8d, respectively. Past research indicated that glucose could be used as a template to fabricate two-dimensional nanosheets. Typically, two-dimensional materials with large SSA and ultrathin characteristics provide unique physical and chemical properties. The G-CoFe₂O₄ sample has a two-dimensional nanosheet structure, the highest SSA, and the smallest grain size overall. XPS spectra of the prepared samples are presented in Figure 9. There are no significant differences

Table 1. BET parameters, Crystallite Size, and Saturation Magnetization of Samples

| Sample       | SSA (m²/g) | Pore diameter (nm) | Pore volume (cm³/g) | Crystallite size (nm) | Ms (emu/g) |
|--------------|------------|--------------------|---------------------|-----------------------|------------|
| CoFe₂O₄     | 2.72       | 10.56              | 0.00562             | 25                    | 77.3       |
| N-CoFe₂O₄   | 4.13       | 11.24              | 0.00883             | 20                    | 48.0       |
| G-CoFe₂O₄   | 52.58      | 11.99              | 0.152445            | 10                    | 42.9       |

Figure 7. SEM micrograph of (a) G-CoFe₂O₄ and (b) N-CoFe₂O₄.

Figure 8. TEM micrographs of (a, b) N-CoFe₂O₄ and (c, d) G-CoFe₂O₄.

Figure 9. XPS spectra of the prepared samples.
between the CoFe$_2$O$_4$, N-CoFe$_2$O$_4$, and G-CoFe$_2$O$_4$ samples. A survey scan of all products indicates the presence of Co 2p, Fe 2p, C 1s, and O 1s phases. These results indicate that the phases of the prepared samples are unaffected by the additives (NH$_4$HCO$_3$ and glucose). However, based on an increase in pores, the Ms values of the N-CoFe$_2$O$_4$ and G-CoFe$_2$O$_4$ are reduced. The Ms values of the N-CoFe$_2$O$_4$ and G-CoFe$_2$O$_4$ samples are 48.0 and 42.9 emu/g, respectively.

The photo-Fenton catalytic activity of the N-CoFe$_2$O$_4$ and G-CoFe$_2$O$_4$ samples was investigated based on the degradation of MB under the same conditions. As shown in Figure 10, 5 mg of G-CoFe$_2$O$_4$ degrades the MB in 40 min and 5 mg of N-CoFe$_2$O$_4$ degrades the MB in 25 min. One can see that the catalytic activity of CoFe$_2$O$_4$ is significantly enhanced by NH$_4$HCO$_3$ and glucose. Based on eqs 2 and 3, this enhancement can be attributed to the large number of pores formed in the products. A mesoporous structure with a high SSA is suitable for MB molecular transfer and the generation of highly accessible multichannel reaction sites for adsorption and degradation. Degradation activity is defined by reactions (eqs 4−8) between the surface Fe$^{3+}$ on the CoFe$_2$O$_4$ and H$_2$O$_2$.

$$\text{Fe}^{3+} + h_{\text{VB}} + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + \text{H}^+ + \cdot\text{OH}$$ (4)

$$\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \cdot\text{OH}^- + \cdot\text{OH} + \text{Fe}^{3+}$$ (5)

$$\text{CoFe}_2\text{O}_4 + 2\text{hv} \rightarrow \text{e}_{\text{CB}}^- + h_{\text{VB}}^+$$ (6)

$$\text{Fe}^{3+} + \text{e}_{\text{CB}}^- \rightarrow \text{Fe}^{2+}$$ (7)

$$\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \cdot\text{OH}^- + \cdot\text{OH}$$ (8)

Furthermore, based on its magnetic behavior, the catalyst is easy to recycle. As shown in Figure 11, N-CoFe$_2$O$_4$ particles can be rapidly separated from the solution using an external magnet. This indicates that N-CoFe$_2$O$_4$ particles can be used as a recyclable catalyst. To analyze the chemical stability of the N-CoFe$_2$O$_4$ particles, the recycling catalytic degradation of N-CoFe$_2$O$_4$ particles was observed under the same conditions described above for four cycles, as shown in Figure 12. One can clearly see that the MB degradation efficiencies over three cycles of 25 min are 98, 96, and 95%. Therefore, the degradation activity of the N-CoFe$_2$O$_4$ particles exhibits no significant decrease over three cycles. These results demonstrate that magnetic CoFe$_2$O$_4$ nanoparticles have excellent potential as recyclable photo-Fenton catalysts for the removal of organic dyes. This facile strategy can offer an effective technique for the preparation of other binary catalysts with mesoporous structures for treatment of wastewater.

3. CONCLUSIONS

CoFe$_2$O$_4$ nanoparticles with a cubic spinel structure were successfully synthesized via SCS in one step. The fuel-to-ferric nitrate ratio determined the phase composition and magnetic properties of the CoFe$_2$O$_4$ nanoparticles. When this ratio was 0.8, the as-prepared product was pure CoFe$_2$O$_4$ with an average
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tionally, the synthesized magnetic CoFe₂O₄ catalyst exhibited excellent recyclability. The method presented in this article provides a simple and highly efficient method for the mass production of magnetic CoFe₂O₄ catalysts with mesoporous structures as well as other binary catalysts.

4. EXPERIMENTAL SECTION

4.1. Synthesis. In our experimental process, all used reagents were of analytical grade. Ferric nitrate (Fe(NO₃)₃·9H₂O) was used as an Fe source, and cobalt nitrate (Co(NO₃)₂·6H₂O) was used as a Co source. First, 8 g of ferric nitrate, 3 g of cobalt nitrate, and various amounts of glycine were mixed in 100 mL of distilled water in a 500 mL glass. The tunable parameter (φ) was the molar ratio between glycine and ferric nitrate (φ = 0.6, 0.7, 0.8, and 0.9). Based on the chemical propellant theory, which is the underlying principle of SCS, the stoichiometric ratio was φ = 1. The glass was then heated in the air using an electrical furnace. The heated temperature is 150 °C. As heating continued, free water evaporated and the solution formed a gel. Next, an instantaneous combustion exothermic reaction occurred. The entire process only required around 10–15 min, and the final product was prepared directly. The reaction process is illustrated in Figure 13.

4.2. Characterizations. The prepared products were characterized using X-ray diffraction (XRD) (Rigaku D/max-RB12) and X-ray photoelectron spectroscopy (XPS; PerkinElmer). Thermal characteristics were investigated under flowing air at a heating rate of 10 °C/min using thermogravimetry and differential scanning calorimetry (Rigaku, DT-40, Tokyo, Japan). The morphology and particle size of the products were observed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Magnetic properties were measured using vibrating sample magnetometry at room temperature. The specific surface area (SSA) was analyzed via the Brunauer–Emmett–Teller (BET) method using an automated surface area and pore size analyzer (QUADRASORB SI-MP, Quantachrome Instruments, Boynton Beach, FL).

4.3. Catalytic Activity Evaluation. The photo-Fenton catalytic activity of CoFe₂O₄ was investigated based on the degradation of methylene blue (MB) in water with 0.5 mL of H₂O₂ under simulated sunlight irradiation (150 W halogen lamp). The initial concentration of MB was 20 ppm, and 5 mg of the prepared product was used as a catalyst. The MB solution volume was 100 mL and was ultrasonically treated for 30 min in the dark. The concentration of MB over irradiation time was tested at a special wavelength (664 nm) by using a UV-1200 spectrophotometer.

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REFERENCES

(1) Brillas, E. A review on the photoelectro-Fenton process as efficient electrochemical advanced oxidation for wastewater remediation treatment with UV light, sunlight, and coupling with conventional and other photo-assisted advanced technologies. Chemosphere 2020, 250, 126198.

(2) Monteoliva-García, A.; Martín-Pascual, J.; Muñio, M. M.; Poyatos, J. M. Effects of carrier addition on water quality and pharmaceutical removal capacity of a membrane bioreactor-Advanced oxidation process combined treatment. Sci. Total Environ. 2020, 708, 135104.

(3) Pei, R.; Fan, L.; Zhao, F.; Xiao, J.; Yang, Y.; Lai, A.; Zhou, S.-F.; Zhao, G. 3D-Printed metal-organic frameworks within biocompatible polymers as excellent adsorbents for organic dyes removal. J. Hazard. Mater. 2020, 384, 121418.

(4) Hao, N.; Nie, Y.; Xu, Z.; Jin, C.; Fyda, T. J.; Zhang, X. J. Microfluidics-enabled acceleration of Fenton oxidation for degradation of organic dyes with rod-like zero-valent iron nanoassemblies. J. Colloid Interface Sci. 2020, 559, 254–262.

(5) Cai, Q.; Wu, M. Y.; Li, R.; Deng, S. H.; Lee, B. C. Y.; Ong, S. L.; Hu, J. Y. Potential of combined advanced oxidation-Biological process for cost-effective organic matters removal in reverse osmosis concentrate produced from industrial wastewater reclamation: Screening of AOP pre-treatment technologies. Chem. Eng. J. 2020, 389, 123419.
(6) Han, R.; Zhang, Y.; Xie, Y. Application of Mn3O4 nanowires in the dye waste water treatment at room temperature. Sep. Purif. Technol. 2020, 234, 116119.

(7) Li, X.; Liu, X.; Lin, C.; Zhang, H.; Zhou, Z.; Fan, G.; Ma, J. Cobalt ferrite nanoparticles supported on drinking water treatment residuals: An efficient magnetic heterogeneous catalyst to activate peroxymonosulfate for the degradation of atrazine. Chem. Eng. J. 2019, 367, 208–218.

(8) He, D.; Q.; Zhang, Y. J.; Pei, D. N.; Huang, G. C.; Liu, C.; Li, J.; Yu, H. Q. Degradation of benzoic acid in an advanced oxidation process: The effects of reducing agents. J. Hazard. Mater. 2020, 382, 121090.

(9) Amiri, M.; Akbari, A.; Ahmadi, M.; Pardakhti, A.; Salavat-Niasari, M. Synthesis and in vitro evaluation of a novel magnetic drug delivery system; procoecological method for the preparation of CoFe2O4 nanostructures. J. Mol. Liq. 2018, 249, 1151–1160.

(10) Cernea, M.; Galizia, P.; Ciuchi, I.; Aldica, G.; Mihalache, V.; Diamandescu, L.; Galassi, C. CoFe2O4 magnetic ceramic derived from gel and densified by spark plasma sintering. J. Alloy. Compd. 2016, 656, 854–862.

(11) Han, X.; Liu, S.; Huo, X.; Cheng, F.; Zhang, M.; Guo, M. Facile and large-scale fabrication of (Mg,Ni)(Fe,Al)O4 heterogeneous photo-Fenton-like catalyst from saprolite laterite ore for effective removal of organic contaminants. J. Hazard. Mater. 2020, 392, 122295.

(12) Yang, J.; Zhang, Y.; Zeng, D.; Zhang, B.; Hassan, M.; Li, P.; Qi, C.; He, Y. Enhanced catalytic activation of photo-Fenton process by CuO/MnOx/FeO4 for effective removal of organic contaminants. Chemosphere 2020, 247, 125780.

(13) Xie, A.; Cui, J.; Yang, J.; Chen, Y.; Lang, J.; Li, C.; Yan, Y.; Dai, J. Graphene oxide/Fe(III)-based metal-organic framework membrane for enhanced water purification based on synergistic separation and photo-Fenton processes. Appl. Catal. B 2020, 264, 118548.

(14) Sun, M.; Han, X.; Chen, S. Synthesis and photocatalytic activity of nano-cobalt ferrite catalyst for the photo-degradation various dyes under simulated sunlight irradiation. Mater. Sci. Semicond. Process. 2019, 91, 367–376.

(15) Liu, Y.; Chen, Z.; Zhang, Y.; Feng, R.; Chen, X.; Xiong, C.; Dong, L. Broadband and lightweight microwave absorber constructed by in situ growth of hierarchical CoFe2O4-reduced graphene oxide porous nanocomposites. ACS Appl. Mater. Interfaces 2018, 10, 13860–13868.

(16) Rao, K. S.; Nayakulu, S. V. R.; Varma, M. C.; Choudary, G. S. V. Rao, K. H. CoFe2O4 nanoparticles synthesized by PVA assisted sol-gel method. J. Magn. Magn. Mater. 2018, 451, 602–608.

(17) Wu, K.; Liu, D.; Tang, Y. In-situ single-step chemical synthesis of graphene-decorated CoFe2O4 composite with enhanced Li ion storage behaviors. Electrochim. Acta 2018, 263, 515–523.

(18) Abbasian, A. R.; Rahmani, M. Salt-assisted solution combustion synthesis of nanostructured ZnFe2O4−ZnAs powders. Inorg. Chem. Commun. 2020, 111, 107629.

(19) Wu, H.; Qin, M.; Cao, Z.; Li, X.; Jia, B.; Chen, P.; Huang, M.; Qi, X. Magnetic iron nanoparticles prepared by solution combustion synthesis and hydrogen reduction. Chem. Phys. Lett. 2018, 706, 7–13.

(20) Ahmad, I.; Akhtar, M. S.; Ahmed, E.; Ahmad, M.; Keller, V.; Khan, W. Q.; Khalid, N. R. Rare earth co-doped ZnO photocatalysts: Solution combustion synthesis and environmental applications. Sep. Purif. Technol. 2020, 237, 116328.

(21) Aliahsaghi, H.; Arabi, A. M.; Haratizadeh, H. A novel approach for solution combustion synthesis of tungsten oxide nanoparticles for photocatalytic and electrochemical applications. Ceram. Int. 2020, 46, 403–414.

(22) Yilmaz, E.; Sonmez, M. S. The influence of process parameters on the chemical and structural properties of solution combustion prepared vanadium pentoxide. Mater. Lett. 2020, 261, 127095.

(23) Hu, D.; Zhao, F.; Zhang, Z.; Miao, L.; Ma, R.; Zhao, W.; Ren, L.; Zhang, G.; Zhai, L.; Wang, D.; Dou, S. Synthesis and magnetic properties of monodisperse CoFe2O4 nanoparticles coated by SiO2. Ceram. Int. 2018, 44, 22462–22466.

(24) Gonzalez-Sandoval, M. P.; Beasley, A. M.; Miki-Yoshida, M.; Fuentes-Cobas, L. F.; Matutes-Aquino, J. A. Comparative study of the microstructural and magnetic properties of spinel ferrites obtained by co-precipitation. J. Alloys Compd. 2004, 369, 190–194.

(25) Tripathi, B. M.; Mohanty, T.; Prakash, D.; Tyagi, A. K.; Sinha, P. K. Glycine-nitrate solution combustion synthesis of lithium zirconate: Effect of fuel-to oxidant ratio on phase, microstructure and sintering. J. Eur. Ceram. Soc. 2020, 40, 136–144.

(26) Lannelongue, P.; Le Vot, S.; Fontaine, O.; Sougrati, M.; Crossnier, O.; Brousse, T.; Favier, F. Investigation of Ba0.5Sr0.5CoFe1−xO3−δ as a pseudocapacitive electrode material with high volumetric capacitance. Electrochim. Acta 2018, 271, 677–684.

(27) Prasad, P. D.; Hemalatha, J. Enhanced magnetic properties of highly crystalline cobalt ferrite fibers and their application as gas sensors. J. Magn. Magn. Mater. 2019, 484, 225–233.

(28) Cuong, N. D.; Trung, K. Q.; Nguyen, T. D.; Van Toan, N.; Hung, C. M.; Van Hiue, N. Controlled synthesis of manganese tungstate nanorods for highly selective NH3 gas sensor. J. Alloys Compd. 2018, 735, 787–794.

(29) Zhang, G.; Xu, Q.; Liu, Y.; Qin, Q.; Zhang, J.; Qi, K.; Chen, J.; Wang, Z.; Zheng, K.; Swierczek, K.; Zheng, W. Red phosphorus as self-template to hierarchical nanoporous nickel phosphides toward enhanced electrocatalytic activity for oxygen evolution reaction. Electrochim. Acta 2020, 332, 135500.

(30) Sheng, Z. M.; Huang, H.; Niu, R. L.; Han, Z. W.; Jia, R. P. M-Nx (M = Fe, Co, Ni, Cu) doped graphitic nanocages with high specific surface area for non-enzymatic electrochemical detection of H2O2. Sens. Actuators B 2020, 305, 127550.

(31) Cao, Z.; Qin, M.; Jia, B.; Zhang, L.; Wan, Q.; Wang, M.; Volinsky, A. N.; Xu, X. Facile route for synthesis of mesoporous Cr2O3 sheet as anode material s for Li-ion batteries. Electrochim. Acta 2014, 139, 76–81.

(32) Cao, Z.; Qin, M.; Zuo, C.; Gu, Y.; Jia, B. Facile route for synthesis of mesoporous graphite encapsulated iron carbide/iron nanosheet composites and their electrocatalytic activity. J. Colloid Interface Sci. 2017, 491, 55–63.

(33) Chen, X.; Ahn, J. H. Biodegradable and bioabsorbable sensors based on two-dimensional materials. J. Mater. Chem. B 2020, 8, 1082–1092.

(34) Liu, C.; Wang, Y.; Li, H.; Wu, Y.; Li, Y.; Li, J.; He, K.; Xu, Y.; Zhang, J.; Wang, Y. Robust anion exchanger and cation exchanger phases in a two-dimensional antiferromagnetic topological insulator. Nat. Mater. 2019, 19, 522–527.

(35) Han, X.; Chen, T.; Li, J.; Cheng, F.; Zhang, M.; Guo, M. Synthesis of (Ni,Mg,Cu)Fe2O4 from nickel sulphide ore: A novel heterogeneous photo-Fenton-like catalyst with enhanced activity in the presence of oxalic acid. J. Photochem. Photobiol., A 2020, 390, 112308.

(36) Zhang, Y.; Fang, H.; Zhang, Y.; Wen, M.; Wu, D.; Wu, Q. Active cobalt induced high catalytic performances of cobalt ferrite nanobrushes for the reduction of p-nitrophenol. J. Colloid Interface Sci. 2019, 535, 499–504.