Preparation and characterization of ZnO/graphene/graphene oxide/multi-walled carbon nanotube composite aerogels

Yang Shen1*, Zhihao Yuan1, Fengjiao Cheng2, Zhen Cui3*, Deming Ma3, Yueyue Bai1, Shuqing Zhao1, Jieyao Deng1 and Enling Li1*

1School of Science, Xi'an University of Technology, Xi'an, China, 2School of Electrical Engineering, Xi'an University of Technology, Xi'an, China, 3School of Automation and Information Engineering, Xi'an University of Technology, Xi'an, China

ZnO/Graphene (G)/Graphene Oxide (GO)/Multi-walled Carbon Nanotube (MCNT) composite aerogels with a three-dimensional porous structure were prepared by the sol-gel method under average temperature and alkaline conditions, combined with freeze-drying process and heat treatment process. The photocatalytic degradation of Rhodamine B (RhB) was mainly studied. The scanning electron microscope (SEM) test results showed that the morphology uniformity of the ZnO/G/GO/MCNT composite aerogel was significantly enhanced, which effectively solving the agglomeration problem of MCNT and ZnO. The photocatalytic degradation test results of RhB show that due to the synergistic effect of physical adsorption and photocatalytic degradation, the total degradation efficiency of RhB by ZnO/G/GO/MCNT could reach 86.8%, which is 3.3 times higher than that of ZnO. In addition, the synergistic effect of ZnO and G effectively hinders the recombination of photo-generated electron-hole pairs and enhances photocatalytic activity. The ZnO/G/GO/MCNT composite aerogel can be applied in the visible light catalytic degradation of water pollution.

KEYWORDS
ZnO, graphene, multi-walled carbon nanotube, aerogels, photocatalytic

Introduction

In recent years, with the rapid economic development and the increasing environmental pollution (Cui et al., 2020), the management of organic pollutants in water bodies has attracted great concern (Tang et al., 2022). Traditional methods of treating organic contaminants in wastewater include physical adsorption (Cui et al., 2022a; Das et al., 2022; Wang et al., 2022), chemical oxidation (Li et al., 2021; Yan et al., 2021; Zhang et al., 2021), and biological degradation (Sun K et al., 2021; Marciano et al., 2021; Zou et al., 2021). Compared with traditional methods, photocatalytic technology, as a new “green sustainable technology,” features the advantages of environmental...
Rhodamine B (RhB) C 28H31ClN2O4 Analysis pure

et al., 2019; Zhang and Cui, 2022).

such as titanium oxide (TiO2)( Gopinath et al., 2020; Li et al.,

adsorption, doping, and compounding have also emerged (Cui

Frontiers in Chemistry frontiersin.org02

Shen et al. 10.3389/fchem.2022.992482

The photocatalytic oxidation reaction uses semiconductors,
such as titanium oxide (TiO2) (Gopinath et al., 2020; Li et al.,

oxidizing properties (Sun and Schwingenschlögl, 2021b; Shen

electrons in the valence band (VB) of the semiconductor are

Semiconductor material ( Shen et al., 2022a ). It has high

ZnO is the II-VI direct bandgap novel inorganic

semiconductor material (Shen et al., 2022a). It has high

photocatalytic activity (Yang et al., 2004; Sun C et al., 2018),

cheap availability, and abundant reserves. So its application

(Wang et al., 2018) for efficient photocatalysis (Yan et al.,

one of the hottest research topics at present. However, due to the small size effect, ZnO can achieve high

photocatalytic efficiency only at the nanoscale size. For nanoscale

ZnO, it has a large specific surface area and high specific surface

energy, and it is easy to agglomerate by itself. It has a strong

surface polarity, which makes it difficult to disperse uniformly in

the medium, resulting in few active sites for the photocatalytic

oxidation of ZnO. In addition, ZnO exhibits the characteristics of

a wide bandgap, whose bandgap is about 3.37 eV at room
temperature (Shen et al., 2022b). As a result, it has poor
electrical conductivity and a narrow response range to the solar spectrum. Moreover, although using metals or organic materials as loading materials for ZnO may compensate for these deficiencies, photo corrosion effects cause the loading materials to decompose and

the shedding of catalytic particles, which may result in secondary

pollution to the environment. These factors significantly limit the

photocatalytic performance of ZnO. Therefore, solving the

problems of complex dispersion, poor electrical conductivity,

low solar light utilization, and severe photo corrosion of

nanoscale ZnO is the challenge to achieve a significant

increase in ZnO photocatalytic efficiency and improved
cycling stability.

Graphene oxide (GO) has a high specific area. Its surface is

rich in hydrophilic functional groups, and GO has a good affinity

for dye molecules. So it is easy to achieve uniform dispersion of

GO and adsorption of organic dye molecules dissolved in water.

Removal of hydrophilic functional groups from the surface of

GO, thereby reducing GO to graphene (G), can improve the

electrical conductivity of the material.

It is reported that using G as a carrier for ZnO can improve its

photocatalytic properties. Due to the good electrical conductivity

of G, it creates a shallow potential Schottky barrier at the contact

interface between ZnO and G. This reduces the compounding of

photo-generated carriers in ZnO, thus improving the

photocatalytic performance of ZnO. Sun et al. (2019) compounded ZnO with G. They found that this compound

enabled photo-generated charge carrier transfer and effectively

hindered electron-hole pair recombination, degrading 95.9% of

methylen blue dye under UV irradiation conditions for 60 min.

Pant et al. (2013) prepared Ag/ZnO/Reduced Graphene Oxide

(RGO) composites, they found that it has suitable photocatalytic

and antibacterial activities. The efficiency of perfect recovery and

recycling of the catalyst after the reaction remains unchanged. In

addition, Ahmad et al. (2018) combined nickel oxide and RGO to

enhance the photocatalytic activity of the metal oxides. The

formation of P-N heterojunctions and the strong interaction

between nickel oxide and RGO dictated a high separation

efficiency of photo-generated electrons and holes, enhancing

the photodegradation activity of methylene blue dyes. However,

the methods reported in these studies require UV

light to achieve the photocatalytic reaction, indicating the need

for severe conditions of use. Efficient photocatalytic reactions

under visible light require more in-depth research.

Aerogels are nanomaterials with micro, mesoporous and

microporous multilevel fractal network structures (Shen et al.,

2019), which also can provide a good support skeleton for

semiconductors. Besides, it can provide a special contact

TABLE 1 The chemical reagent for preparing the sample.

| Reagent name                        | Chemical formula            | Specification   |
|------------------------------------|-----------------------------|-----------------|
| Zinc acetate dihydrate             | C9H6O3Zn2H2O                | Analysis pure   |
| Sodium hydroxide                   | NaOH                        | Analysis pure   |
| Multi-walled Carbon Nanotubes (MCNT) | C                  | >95 wt%        |
| Graphene Oxide (GO)                |                             | >95 wt%        |
| Rhodamine B (RhB)                  | C12H22ClN2O4                | Analysis pure   |
interface for photocatalytic reactions and accelerate the diffusion of photoelectrons in water (Li and Zhang, 2022).

Here, we have developed a method for assembling ZnO, G, GO, and Multi-Walled Carbon Nanotube (MCNT) into composite aerogels with a three-part porous structure. The composite material allows the nano-ZnO to be uniformly dispersed in water, reducing the compounding of photo-generated carriers in the ZnO, enhancing the electrical conductivity, and enabling efficient photocatalytic reactions to be developed under visible light conditions.

Experimental

Materials

The reagents used in this paper include Zinc acetate dihydrate, sodium hydroxide (NaOH), and Rhodamine B (RhB), which are all analytically pure and purchased from Sinopharm Chemical Reagent Co. Ltd., MCNT and GO are purchased from Suzhou Tanfeng Graphene Technology Co. Ltd., as shown in Table 1.

Preparation of composite aerogels

The preparation process of ZnO/G/GO/MCNT composite aerogel is shown in Figure 1. GO aqueous solution, MCNT aqueous solution, zinc acetate dihydrate solution, and distilled water mixed well at room temperature and pressure. Then, add NaOH solution in 4 equal parts, once at an interval of 1 min, 5–10 ml each time, with a drop acceleration rate of 5–10 drops per second, stirring continuously at room temperature to make the alkali fully react with the mixed solution. And precursor sols were obtained. The precursor sols were vacuum filtered to achieve hydrogels. Next, the hydrogel is placed in a freeze dryer for 1–2 h to ice entirely, then vacuum freeze-dried for 24 h to produce a Zn(OH)₂/GO/MCNT composite aerogel.

Table 2 The raw material ratio of aerogel.

| Sample # | 6 mg/ml MCNT (ml) | 6 mg/ml GO (ml) | 1 mol/L C₆H₅O₄Zn (ml) | 1 mol/L NaOH (ml) |
|----------|------------------|-----------------|----------------------|------------------|
| 1        | 0                | 0               | 2.5                  | 4 × 0.625        |
| 2        | 40               | 0               | 2.5                  | 4 × 0.625        |
| 3        | 20               | 40              | 2.5                  | 4 × 0.625        |
Finally, the Zn(OH)$_2$/GO/MCNT composite aerogel is heat-treated in a thermostat or tube furnace for 1.5 h at 145°C. The Zn(OH)$_2$ decomposes to ZnO, while GO is partially restored to G, obtaining ZnO/G/GO/MCNT composite aerogel.

To accurately describe the properties of ZnO/G/GO/MCNT composite aerogels, different sample ratios are shown in Table 2. ZnO (sample #1), ZnO/MCNT composite aerogel (sample #2), and ZnO/G/GO/MCNT composite aerogel (sample #3).
Characterization

The micrograph of samples was characterized by a scanning electron microscope (SEM, Japan Electronics Corporation, JSM-6700F). X-ray diffractometer (XRD, Shimadzu Japan, XRD-7000) was used to describe the internal atomic or molecular structure of samples. TG-DTA curve of the material using a comprehensive thermal analyzer (Beijing Hengjiu, HCT-3). UV-Visible spectrophotometer (Unico, United States, UV-2355) is used to measure the absorbance of samples at wavelengths between 200 and 800 nm.

The wavelength-absorbance curve is plotted, and the absorption edge is estimated by the tangent method. Using monochromatic light of 200–800 nm to irradiate the composite material, obtaining the light absorption of composite material at different wavelengths. The bandgap \(E_g\) is calculated as follows (Sauer et al., 2002):

\[
E_g = \frac{hc}{\lambda_m}
\]

where \(h\), \(c\), and \(\lambda_m\) denote Planck’s constant, speed of light in a vacuum, and maximum wavelength of absorbed light, respectively. \(\lambda_m\) can be estimated from the UV-Vis absorption spectrum. The absorption efficiency of composite aerogels for sunlight can be obtained by calculating the proportion of wavelengths less than \(\lambda_m\) in the solar range.

The photocatalytic activity of the resulting composite aerogel was investigated by the rapid degradation of RhB under visible light radiation. Firstly, 20 mg of the samples were added into a 100 ml range quartz beaker, and add 50 ml of RhB staining solution at a concentration of 10 mg/L. Secondly, by the water bath method, maintain a speed of 1,000 r/min at 30°C with a heated magnetic mixer to mix well. At the same time, the dark reaction under shade for 30 min to reach adsorption equilibrium. After that, 5 ml of solution from the dark reaction system was taken with a pipette for testing. Then, it was switched on a 350 W xenon cold light source for light reaction, and the light source 13.5 cm from the bottom of the beaker. 5 ml of solution is removed from the photoreaction system every 5 min with a pipette for testing. After six extractions, the test samples were centrifuged, and the absorbance of the supernatant was measured.

According to the Beer-Lambert law, the absorbance \(A\) of a dye solution is proportional to its concentration. In addition, the dye removal rates \(D\) are computed as follows (Cui et al., 2022b):

\[
E_g = \frac{hc}{\lambda_m}
\]
where $C_0$, $C$, $A_0$, and $A$ represent the initial concentration of the fuel solution, the concentration of the dye solution after $t$ minutes, the initial absorbance of the dye solution, and the absorbance of the dye solution after $t$ minutes, respectively. The value of $A_t/A_0$ can be calculated from the relative absorption intensity of the UV-Vis absorption spectrum.

The photocatalytic degradation process of dyes mainly consists of mass transfer and photocatalytic reactions. The kinetic constants of photocatalytic reaction degradation are described by the Langmuir–Hinshelwood model as follows (Sauer et al., 2002):

$$R = -\frac{dC}{dt} = \frac{\kappa KC}{1 + KC}$$

where $R$, $\kappa$, $K$, and $C$ represent the total reaction rate of the dye at time $t$, the Langmuir rate constant, the equilibrium constant for the adsorption and desorption of the dye on the catalyst, and the concentration of the dye at time $t$, respectively. The Eq 3 can be simplified to a primary reaction kinetic model when the concentration of the paint is relatively low. The calculation is as follows (Cui et al., 2022b):

![Figure 6](image1)

Experimental results of photocatalytic degradation of RhB by (A) ZnO (sample #1) and by (B) ZnO/GO/MCNT composite aerogel (sample #3).

![Figure 7](image2)

(A) RhB degradation curve and (B) reaction kinetic curve under visible light for ZnO (sample #1), ZnO/MCNT composite aerogel (sample #2), and ZnO/GO/MCNT composite aerogel (sample #3).
\[
\frac{\ln C_0}{C} = \kappa K t = k_{app} t
\]

(4)

where \(k_{app}\) indicates the primary reaction rate constant. Linear fit of \(\ln (C_0/C)\) and \(t\), and the slope is \(k_{app}\) which can be used to characterize the photocatalytic reaction efficiency quantitatively.

**Results and discussion**

**Morphology and compositional characterization**

To accurately describe the thermal decomposition of Zn(OH)\(_2\), the Thermogravimetry (TG) and Temperature difference (DTA) curves of sample #1 before and after heat treatment are shown in Figures 2A,B, respectively. From Figure 2A, it can be observed that an endothermic peak appears at 124°C, which is mainly due to the absorption of heat by the thermal decomposition of Zn(OH)\(_2\), and the overall weight of the sample is decreasing. From Figure 2B, no vigorous endothermic or exothermic peaks were observed in the range of 0–150°C. Altuntasoglu et al. (2010) performed TG-DTA analysis on Zn(OH)\(_2\). They found an endothermic peak appeared at 134°C, and the final decomposition product was ZnO. Related reports are consistent with our results. Therefore, it proved that Zn(OH)\(_2\), in sample #3, has been completely converted into ZnO. It is consistent with the results of the TG-DTA analysis.

**Optical absorption and photocatalytic degradation of RhB**

To demonstrate the change in the response range of the ZnO/G/GO/MCNT composite aerogel to the solar spectrum, we further studied the UV-Vis absorption spectra of sample #1 and sample #3, which are shown in Figure 5A. The relation between the Kubelka-Munk function and photon energy is shown in Figure 5B. For sample #1, the tangent (extrapolation method) calculates that the absorption edge is around 396 nm. For sample #3, its absorption edge is at 416 nm. Meanwhile, the band gap of samples #1 and #3 are calculated to be 3.135 and 2.984 eV, respectively. The reduction of the band gap may be due to the adsorption between different materials (Sun M et al., 2018; Cui et al., 2021a; Cui et al., 2021b). This will improve the photocatalytic degradation of pollutants by the composite material under visible light conditions.

The photocatalytic efficiency is the focus of our inquiry (Cui et al., 2022b). Sample #3 was subjected to photocatalytic experiments, and its photocatalytic activity was evaluated by comparing its photocatalytic degradation rate to RhB. The experimental results are shown in Figure 6B. –30–0 min is the dark reaction stage, and the light reaction starts from 0 min. To reach the experimental results, the same photocatalytic efficiency experiment was applied to sample #1 (Figure 6A). For sample #3, photocatalytic experiments proved that RhB achieved efficient degradation after 30 min of visible light irradiation.

The reaction curves and photocatalytic kinetics curves of different samples are depicted in Figures 7A,B, respectively. The results indicated that RhB adhered to the sample surface by adsorption within 30 min of the dark reaction phase until the adsorption and desorption reached equilibrium. At this stage, it mainly relies on the van der Waals forces between molecules to reach equilibrium quickly, and the adsorption or desorption process is physical adsorption. Besides, compared with sample...
#1, the physical adsorption is enhanced due to the introduction of MCNT, G, and GO. In the photoreaction stage, after 30 min, the degradation efficiency of ZnO (sample #1) was only 26.3%, and the degradation effect was the worst. The degradation efficiency of ZnO/MCNT composite aerogel (sample #2) was 70.8%, and the degradation effect was good. The degradation efficiency of ZnO/G/GO/MCNT composite aerogel (sample #3) is as high as 86.8%, and the degradation effect is the best. Cui et al. (2022b) reported a degradation rate of 99.4% at 90 min for g-C3N4/MoS2 composites. Similar results can be obtained based on the trend of our results. In addition, it can be observed from Figure 7B that the degradation rate of sample #3 accelerates from the photoreaction for 10 min, and it is also the fastest overall among all samples. Figure 8 more intuitively compares the kinetic reaction constants of each sample. It can be observed that the reaction kinetic constant of ZnO/G/GO/MCNT (sample #3) is 0.02497, which is larger than that of ZnO (0.00718, sample #1) and ZnO/MCNT composite aerogel (0.00706, sample #2). In conclusion, compared with single ZnO, the physical adsorption effect, photocatalytic degradation efficiency, and photocatalytic degradation rate of the ZnO/G/GO/MCNT composite aerogels were significantly improved. And it have higher application value.

Conclusion

ZnO/G/GO/MCNT composite aerogels with a three-dimensional porous structure were prepared by the sol-gel method under average temperature and alkaline conditions, combined with a freeze-drying and heat treatment process. The photocatalytic degradation of RhB was mainly investigated. The SEM test results show that the morphology uniformity of the ZnO/G/GO/MCNT composite aerogel is significantly enhanced, effectively solving the agglomeration problem of MCNT and ZnO. TG-DTA analysis and XRD pattern showed that Zn(OH)2 was wholly decomposed into ZnO after heat treatment. The physical adsorption capacity of ZnO/G/GO/MCNT for RhB is significantly improved. And its total degradation efficiency can reach 86.8%, which is 3.3 times higher than that of ZnO (26.3%), indicating that the ZnO/G/GO/MCNT composite aerogels have high photocatalytic activity. In addition, the synergistic effect of ZnO and G can also enable photogenerated carrier transfer to hinder electron-hole pair recombination, enhancing the photocatalytic activity effectively. Therefore, the ZnO/G/GO/MCNT composite aerogel can be applied in the visible light catalytic degradation of water pollution.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

YS, ZC, and EL contributed to conception and design of the study. ZY organized the database. FC and DM performed the statistical analysis. YS and ZY wrote the first draft of the manuscript. YB, SZ, and JD wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was funded by Natural Science Basic Research Program of Shaanxi (Program No. 2022JM-176), Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 21JK0789), the Opening Project of Shanghai Key Laboratory of Special Artificial Microstructure Materials and Technology (Program No. ammt2020A-6), College Students’ Innovative Entrepreneurial Training Plan Program (Program No. 202210700008 and Program No. 202210700105), the National Natural Science Foundation of China (No. 12104362) and China Postdoctoral Science Foundation (Program No. 2020M683684XB).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Ahmad, J., Majid, K., and Dar, M. A. (2018). Controlled synthesis of p-type NiO/n-type GO nanocomposite with enhanced photocatalytic activity and study of temperature effect on the photocatalytic activity of the nanocomposite. Appl. Surf. Sci. 457, 417–426. doi:10.1016/j.apsusc.2018.06.200
Alttuntasoglou, O., Matsuda, Y., Ida, S., and Matsumoto, Y. (2010). Syntheses of zinc oxide and zinc hydroxide single nanosheets. *Chem. Mat.* 22 (10), 3158–3164. doi:10.1021/cm100152q

Cui, Z., Luo, Y., Yu, J., and Xu, Y. (2021a). Tuning the electronic properties of Mo6I4N2 by molecular doping: A first principles investigation. *Phys. E Low-dimensional Syst. Nanotechnologies* 134, 114873. doi:10.1016/j.physe.2021.114873

Cui, Z., Wang, M., Lynn, N., Zhang, S., Ding, Y., and Bai, K. (2021b). Electronic, magnetism and optical properties of transition metals adsorbed packed g-ZnSe. *Superlattices Microstruct.* 152, 106852. doi:10.1016/j.spmi.2021.106852

Cui, Z., Ren, K., Zhao, Y., Wang, X., Shu, H., Yu, J., et al. (2019). Electronic and optical properties of van der Waals heterostructures of g-ZnO nanorods: combined tunability and enhanced photocatalytic activity. *Crystals* 9 (20), 11944. doi:10.3390/crystals91211944

Cui, Z., Wang, S., Wang, L., and Yang, K. (2022a). Optoelectronic and magnetic properties of transition metals adsorbed Pd3Se5 monolayer. *Micro Nanosystes* 167, 207260. doi:10.1016/j.micronano.2022.207260

Cui, Z., Wu, H., Bai, K., Chen, X., Li, L., Shen, Y., et al. (2022b). Fabrication of a g-C3N4/MoS2 photocatalyst for enhanced RhB degradation. *Phys. E Low-dimensional Syst. Nanotechnologies* 144, 115561. doi:10.1016/j.physe.2022.115561

Das, R., Lindström, T., Sharma, P. R., Chi, K., and Hsiao, B. S. (2022). Nanocellulose for sustainable water purification. *Chem. Rev.* 1 (2), 8936–9031. doi:10.1021/acs.chemrev.0c00132

Dong, H., Li, L., Wang, X., Xia, Y., Zhang, Y., and Li, J. (2020). Adsorption of CO, NH3, NO, and NO2 on pristine and defective g-ZnO: Improved gas sensing and functionalization. *Adv. Surf. Sci.* 530, 147275. doi:10.1016/j.apsusc.2020.147275

Dong, H., Dong, Z., and Dong, Y. (2019). Exceptional optical absorption of buckled arsenene covering a broad spectral range by molecular doping. *ACS omega* 5 (3), 8514–8520. doi:10.1021/acsomega.8b02747

Hou, H., Cui, M., Chen, C., Zhu, S., Zhang, L., and Shang, P. (2019). Study on mechanism of photocatalytic performance enhancement for RGO loaded nano-ZnO composites. *Mat. Sci. (9) 4, 428–435. doi:10.21667/acs.mat.2019.94055

Kong, H., Dong, L., Liu, J., Lati, A., Li, S., Chu, G., et al. (2021). *Trametes versicolor* laccase-assisted oxidative coupling of estrogens: Conversion kinetics, linking mechanisms, and practical applications in water purification. *Sci. Total Environ.* 782, 146917. doi:10.1016/j.scitotenv.2021.146917

Sun, M., Luo, Y., Yan, Y., and Schwingenschlogl, U. (2021). Ultralight carrier mobility in the two-dimensional semiconductors Mo5S4, Mo5Se4, and Mo5Te4. *J. Mat. Chem. A Mat.* 9 (16), 6475–6485. doi:10.1039/d1ta01824

Sun, M., and Schwingenschlogl, U. (2020). δ-CS: A direct-band-gap semiconductor combining axiety, ferroelasticity, and potential for high-efficiency solar cells. *Phys. Rev. Appl.* 14 (4), 044015. doi:10.1103/physrevapplied.14.044015

Sun, M., and Schwingenschlogl, U. (2021a). Structure prototype outperforming MXenes in stability and performance in metal-ion batteries: A high throughput study. *Adv. Energy Mater.* 11 (14), 2003633. doi:10.1002/aenm.202003633

Sun, M., and Schwingenschlogl, U. (2021b). Unique nonindirecional slight Poisson’s ratio in δ-phase carbon monohalogenides. *Phys. Chem. C* 125 (7), 4133–4138. doi:10.1021/acs.jpcc.0c11555

Tang, W., Fei, Y., Zheng, H., Zhang, Y., Shu, L., and Zhang, H. (2022). Twenty years of China’s water pollution control: Experiences and challenges. *Chemosphere* 291 (17), 25748–25758. doi:10.1016/j.chemosphere.2022.133875

Wang, F., Wu, P., Shu, L., Huang, D., and Liu, H. (2022). High-efficiency adsorption of Cd (II) and Co (II) by ethylenediaminetetraacetic dianhydride-modified orange peel as a novel synthesized adsorbent. *Environ. Sci. Pollut. Res.* 29 (17), 146917. doi:10.1016/j.envsci.2022.146917

Wang, S., Kuang, P., Cheng, B., Yu, J., and Jiung, C. (2018). ZnO hierarchical microsphere for enhanced photocatalytic activity. *J. Alloys Compd.* 741, 622–632. doi:10.1016/j.jallcom.2018.01.141

Yan, B., Wang, Y., Jiang, X., Liu, K., and Guo, L. (2017). Flexible photocatalytic composite film of ZnO-microrods/polypyrrole. *Adv. Mat. Interfaces* 9 (34), 2913–2919. doi:10.1002/smll.201704153

Yan, H., Lai, C., Wang, D., Liu, S., Li, X., Zhou, X., et al. (2021). *In situ* chemical oxidation: Peroxide or persulfate coupled with membrane technology for wastewater treatment. *J. Mat. Chem. A Mat.* 9 (20), 11994–11960. doi:10.1039/d9ta10063h

Yang, J., Li, A., Hong, W., Park, W. J., Yi, G. C., and Choi, W. (2004). *Photocatalysis using ZnO thin films and nanoneedles grown by metal-organic chemical vapor deposition.* Adv. Mat. 16 (18), 1661–1664. doi:10.1002/adma.200302663

Yin, L., Hai, X., Chang, K., Ichihara, F., and Ye, J. (2018). Synergetic exfoliation and lateral size engineering of MoS2 for enhanced photocatalytic hydrogen generation. *Small* 14 (17), 1401536. doi:10.1002/smll.201704153

Zhang, L., and Cui, Z. (2022). Theoretical study on electronic, magnetic and optical properties of non-metal atoms adsorbed onto germanium carbide. *Nanomaterials* 12 (10), 1712. doi:10.3390/nano12101712

Zhang, M., Yang, Y., An, X., and Hou, L.-a. (2021). A critical review of g-C3N4-based photocatalytic membrane for water purification. *Chem. Eng. J.* 412, 128663. doi:10.1016/j.cej.2021.128663

Zhou, M., Sun, Z., Pujitukul, M., and Majima, T. (2018). Z–scheme photocatalytic water splitting on a 2D heterostructure of black phosphorus/bismuth vanadate using visible light. *Angew. Chem. Int. Ed. Engl.* 57 (8), 2182–2186. doi:10.1002/ange.201711357

Zou, Y., Wu, X., Li, H., Yang, L., Zhang, C., Wu, H., et al. (2021). Metal-phenolic network coated cellulose foams for solar-driven clean water production. *Carbohydr. Polym.* 254, 117404. doi:10.1016/j.carbpol.2021.117404

Sun, C., Xu, Q., Xie, Y., Ling, Y., and Hou, Y. (2018). Designed synthesis of anatase–TiO2 (B) biphase nanowire/ZnO nanoparticle heterojunction for enhanced photocatalysis. *J. Mat. Chem. A Mat.* 6 (18), 8289–8298. doi:10.1039/c7ta10274g

Sun, M., Chou, J. P., Gao, J., Cheng, Y., Hu, A., Tang, W., et al. (2018). Exceptional optical absorption of buckled arsenene covering a broad spectral range by molecular doping. *ACS omega* 3 (8), 8514–8520. doi:10.1021/acsomega.8b02747

Shen et al. 10.3389/fchem.2022.992482