



Article

Facile Fabrication of Porous $\text{Y}_2\text{Zr}_2\text{O}_7$ Nanoparticles with Enhanced Photocatalytic Performance by Citrate-Gel-Combustion Method

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Abstract: $\text{Y}_2\text{Zr}_2\text{O}_7$, as a defect fluorite structure material, has found a wide range of applications in thermal barrier coatings, nuclear waste treatment, luminescent materials and photocatalysis. However, due to the high binding energy, the synthesis of high purity $\text{Y}_2\text{Zr}_2\text{O}_7$ nanomaterials with uniform, fine, and highly active surfaces at low temperatures still remains a challenge. In this work, we successfully developed an effective protocol for preparing porous $\text{Y}_2\text{Zr}_2\text{O}_7$ nanoparticles (NPs) by a facile and environmentally friendly citrate-gel combustion method at the low-temperature of 600 °C, in which citric acid (CA) is used as a chelating agent and fuel at the same time. The $\text{Y}_2\text{Zr}_2\text{O}_7$ nanomaterials show a porous morphology formed by self-assembled NPs with a diameter of 5–10 nm. The porous morphology and photocatalytic ability of $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs can be enhanced by adjusting the CA content. Therefore, the optimal $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs prepared at a molar ratio of CA:Y = 0.8:1 achieved a degradation efficiency of up to 97% after 80 min of UV light irradiation. This work provides a strategy for producing other high-purity metal oxides of the same type in an economical, energy-saving, and large-scale manner.

Keywords: $\text{Y}_2\text{Zr}_2\text{O}_7$; nanoparticles; combustion method; citric acid; photocatalyst

1. Introduction

Compounds with the chemical formula $\text{A}_2\text{B}_2\text{O}_7$ (where A and B are generally a rare earth and/or a transition metal, respectively) have been widely studied by researchers for their unique properties, such as peculiar magnetic properties, low thermal conductivity, fluorescence, and excellent electrochemical properties [1,2]. The crystalline phase structure of an $\text{A}_2\text{B}_2\text{O}_7$ compound could be monoclinic layered perovskite phase, pyrochlore phase, defect fluorite phase, and rare earth C-type phase, which is determined by the r_A/r_B radius ratio [3]. There are a lot of oxygen vacancies and defects in the structure of this kind of material, resulting in wonderful application performance [4,5].

In recent decades, semiconductor photocatalytic materials used for the degradation of wastewater, exhaust gases, and organic pollutants have garnered significant attention [6]. Rare earth zirconates ($\text{Ln}_2\text{Zr}_2\text{O}_7$, where Ln represents lanthanide elements, scandium, and yttrium), as an important class of $\text{A}_2\text{B}_2\text{O}_7$ composite metal oxide



semiconductor materials, have also been found to exhibit excellent photocatalytic activity [7,8]. Thus, their synthesis and performance have become a major focus of research.

Yttrium (Y) and cerium (Ce) are two of the more abundant rare earth elements on Earth, giving Yttrium zirconate ($\text{Y}_2\text{Zr}_2\text{O}_7$) a relative resource advantage over other rare earth zirconates with more limited availability [9]. $\text{Y}_2\text{Zr}_2\text{O}_7$ exhibits a defect fluorite structure with a r_A/r_B ratio of 1.41 at room temperature, belonging to the cubic crystal system with an Fm3m space group [10]. It has been widely reported for applications in thermal barrier coatings, ultrasensitive detection, and fluorescent materials [11–13]. However, there are relatively few studies exploring its potential in photocatalytic applications [14].

The reported methods for synthesizing $\text{Y}_2\text{Zr}_2\text{O}_7$ include the sol-gel method, stearic acid method, co-precipitation method, hydrothermal method, and high-temperature solid-state sintering method [15–21]. The parameters of present work are compared with previous literature and summarized briefly in Table 1. Among these methods, high-temperature solid-state sintering has disadvantages, such as requiring a high synthesis temperature and producing large and uneven nanoparticles (NPs). It also leads to inhomogeneous component distribution, resulting in impure phases and stoichiometric losses. The sol-gel method has the disadvantage of requiring relatively high temperatures for product formation and longer synthesis times. The hydrothermal method has the advantage of overcoming inhomogeneous component distribution and stoichiometric losses, but requires specialized equipment and longer reaction times. More notably, these reported methods often involve long time of ball milling, multiple cleanings by water and ethanol, and high-temperature treatment steps of more than 1000 °C (the externally applied calcination temperature), making the process with the disadvantages of time consuming, energy consuming and uneconomical. Therefore, a simple, lower temperature synthesis of high-purity $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs still needs to be further explored.

Table 1. Comparing parameters of present work with previous literature.

Sample	Synthesis Method	Parameters	Mixing Method	Washing Way	Crystalline Size (nm)	Ref.
$(\text{La}_{1-x}\text{Y}_x)_2\text{Zr}_2\text{O}_7$ ($0 \leq x \leq 1$)	Coprecipitation/calcination method	1200 °C, 12 h (calcination)	Solution, magnetically stirring	With ethanol and DI water	~5000	[15]
Nano-structured Zr alloy ($\text{Y}_2\text{Zr}_2\text{O}_7$ nano-precipitates)	Ball milling and hot-isostatic-pressing (HIP)	400 °C, 4 h (degassing) 800 °C, 8 h (dehydrogenation) 150 MPa, 1000 °C, 4 h (HIP) 800 °C, 3 h (annealing)	Ball milling	/	4.2	[19]
$\text{Y}_2\text{Zr}_2\text{O}_7$	Gel combustion method	500 °C, 5 min (combustion) 900~1300 °C, 1 h (annealing)	Solution, magnetically stirring	/	Nano (~50), bulk (~400)	[13]
$\text{Y}_2\text{Zr}_2\text{O}_7$	Hydrothermal reaction route	200 °C, 20 h (hydrothermal) 1000 °C, 3 h (annealing)	Solution, magnetically stirring	With ethanol and DI water	>10	[21]
$\text{Y}_2\text{Zr}_2\text{O}_7$	Ball milled + heat treatments (HT)	1050 °C, 30 min (annealing)	Ball milling, 5 h	/	/	[22]
$\text{Y}_2\text{Zr}_2\text{O}_7$	Reverse co-precipitation technique	900 °C, 10 min (annealing)	Solution, stirring	Filtration	12 ± 2	[22]
$\text{Y}_2\text{Zr}_2\text{O}_7$	Citrate-gel-combustion method	350 °C, 15 min (combustion) 600 °C, 1 h (annealing)	Solution, magnetically stirring	/	5~10	This work

Herein, we synthesized porous $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs via a facile citrate-gel-combustion method at the condition of 600 °C for 1 h, and investigated the effects of the amount of citric acid (CA) on its morphology and the photocatalytic degradation of Rhodamine B (Rh B) under UV light irradiation. The results showed that the optimal photocatalysts were $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs prepared with a molar ratio of CA:Y = 0.8:1, which achieved a degradation efficiency of up to 97% after 80 min of UV light irradiation. The citrate-gel combustion method developed in this work has several advantages: (i) CA acts as both a chelating agent and a fuel, combines the strengths of the sol-gel method and the self-propagating combustion method, instantaneously releases massive heat, builds a local high-temperature environment to facilitate the formation of high-purity phases, which enables the reaction to proceed rapidly and energy-efficiently; (ii) the strong coordination interaction between CA and metal ions facilitates homogeneous distribution of Y^{3+} and Zr^{4+} species in the precursor gel, thereby regulating the nucleation

and crystal growth behavior of $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs and promoting the formation of uniform particles; (iii) variation in the CA content can effectively regulate the formation of oxygen vacancies and lattice distortion of $\text{Y}_2\text{Zr}_2\text{O}_7$, which can modify the electronic structure and charge-transfer behavior of the $\text{Y}_2\text{Zr}_2\text{O}_7$ photocatalyst; (iv) an appropriate CA:Y ratio achieves a balance among crystallinity, particle size, surface area, and defect concentration, which is beneficial for the separation and migration of photogenerated electron-hole pairs and thus enhances photocatalytic activity; (v) it facilitates the successful synthesis of uniform, fine $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs powder with the advantage of producing no polluting wastewater, making it an environmentally friendly method. This work provides a strategy for producing other high-purity and high-performance rare metal oxides photocatalysts in an economical, energy-saving, and large-scale manner.

2. Experimental

All the reagents used in the experiments were of analytical grade and deionized (DI) water was used throughout the experiment.

2.1. Synthesis of $\text{Y}_2\text{Zr}_2\text{O}_7$

$\text{Y}_2\text{Zr}_2\text{O}_7$ NPs were fabricated by a facile citrate-gel-combustion method. First, $\text{Y}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ and $\text{Zr}(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$ were dissolved in DI water with the molar ratio of 1:1. Then, added the CA drop by drop to the mixed solution above, and the molar ratio of CA and Y ion should be kept at (0.2~1.6):1. Stirred continuously until a stable sol is formed, then transferred the sol solution into a thermostatic magnetic stirring vessel, maintained the temperature at 80 °C and stirred for 5 h. The obtained white xerogel precursor was collected to the alumina crucible and reacted for 15 min in muffle furnace at the temperature of 350 °C for the first combustion stage. And then, grinded the obtained porous block into uniform powder at an agate mortar for 5 min, which is then put into muffle furnace again for calcination to remove the carbon impurities under the setting condition of 600 °C for 1 h. Finally, the uniform white powder products were obtained.

2.2. Characterizations

The crystalline phase composition of the samples was characterized by a powder X-ray diffraction (XRD, Rigaku D/max-2000, Tokyo, Japan) with Cu K α radiation ($\lambda = 0.15406$ nm). The morphology structure analysis of the products was performed by field emission scanning electron microscopy (FE-SEM, Hitachi, Tokyo, Japan, S-4800) and transmission electron microscope (TEM, Tecnai G² F20, Waltham, MA, USA). The absorption properties of the samples were recorded on a UV/vis/NIR spectrophotometer (Agilent Cary 5000, Cary, NC, USA), which BaSO_4 was used as a reflectance standard. And the photoluminescence (PL) spectra were measured on a spectrofluorometer (Edinburgh FS5, Livingston, UK) at room temperature.

2.3. Photocatalytic Degradation of Rhodamine B

The photocatalytic activities of as-prepared $\text{Y}_2\text{Zr}_2\text{O}_7$ photocatalysts were evaluated by photocatalytic degradation of organic dye Rh B under UV light irradiation of a 500 W Hg lamp. In a typical process, 10 mg powder was added to 50 mL of Rh B aqueous solution with the concentration of 10 mg/L implemented on BL-GHX-V photocatalytic customized quartz reactor (BILON, Co. Ltd., Xi'an, China), and the pH was at the natural value without further adjustment. Meanwhile, the reaction temperature was maintained at 15 °C during the overall degradation procedure. After 5 min of ultrasonic dispersion, the suspensions were magnetically stirred in the dark for 20 min to reach adsorption/desorption equilibrium before the mixture was exposed to UV light irradiation. Every interval for a period time, 5 mL of the solution was collected by centrifugation (9000 rpm, 5 min), and the concentration of Rh B was determined by UV-vis spectrophotometry (Unico, UV-2600, Shanghai, China) at 553 nm by monitoring its characteristic absorption. The photocatalytic efficiency was determined by C/C_0 , where C is the remained Rh B concentration and C_0 is the concentration at the irradiation time of 0 min. Rh B dissolved in DI water without $\text{Y}_2\text{Zr}_2\text{O}_7$ added was used as a reference sample (noted as: blank).

3. Results and Discussion

Samples with different CA addition were synthesized by citrate-gel-combustion method, and the resultant products were listed in Table 2.

Figure 1 shows schematic illustration of the fabrication of porous $\text{Y}_2\text{Zr}_2\text{O}_7$ by citrate-gel-combustion method. In the first combustion step, xerogel samples with CA addition were burned in a self-propagating manner at a relatively low temperature of 350 °C for 15 min. Then, the resulting porous block was ground into uniform powder

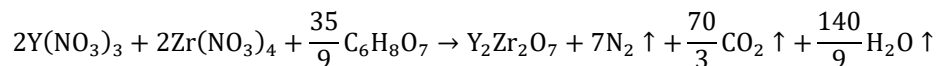
and calcined again at 600 °C for 1 h to remove impurity carbon that produced from the first combustion step. Finally, the pure $Y_2Zr_2O_7$ powder was obtained.

Table 2. Samples synthesized with different CA content.

Ref.	Samples
CY0.2	$Y_2Zr_2O_7$ (CA:Y = 0.2:1)
CY0.4	$Y_2Zr_2O_7$ (CA:Y = 0.4:1)
CY0.8	$Y_2Zr_2O_7$ (CA:Y = 0.8:1)
CY1.2	$Y_2Zr_2O_7$ (CA:Y = 1.2:1)
CY1.6	$Y_2Zr_2O_7$ (CA:Y = 1.6:1)

In the process of the precursor preparation, CA and metal ions in the reactants were closely contacted and complexed in the liquid system, forming a stable cross-linked precursor xerogel after the sol-gel reaction. And then, during the first combustion step, the carbonyl groups (C=O) in CA and nitrate ions in the reactants played the role of reductants and oxidants in the process of xerogel combustion, respectively. This non-explosive redox reaction can produce a large number of gases, and can obtain NPs with high specific surface area. Finally, low temperature self-propagating combustion generated a large amount of heat instantaneously, which promoted the formation of $Y_2Zr_2O_7$ NPs in an energy-saving way.

Under the assumption of complete combustion of the xerogel, the gases obtained should be N_2 , CO_2 , and H_2O , and the reaction equation can be written as follows:



Due to the time of first combustion step is relative short, a lot of carbon impurities and residual CA remained in the system. After the second step of calcination, the residual carbon and CA impurities were removed and the phase was purified, which promoted the formation of highly crystalline $Y_2Zr_2O_7$.

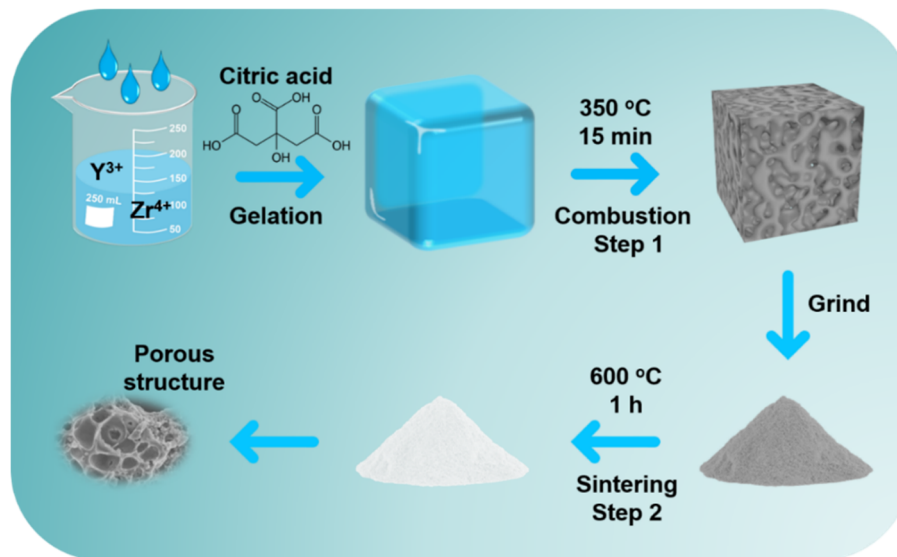


Figure 1. Schematic illustration of the fabrication of porous $Y_2Zr_2O_7$ by citrate-gel-combustion method.

Figure 2a shows the XRD patterns of $Y_2Zr_2O_7$ prepared with different doping content of CA, all the four main peaks (222), (400), (440) and (622) are in agreement with the formation of fluorite structured $Y_2Zr_2O_7$, no impurity peaks were observed, indicating that the citrate-gel-combustion method successfully produces pure $Y_2Zr_2O_7$. It is known that the (222), (400), (440), and (622) peaks are characteristic of the defect fluorite structure. Although these peaks also appeared in the pyrochlore structure, the pyrochlore structure additionally exhibits peaks at (331) ($2\theta = 36.3^\circ$) and (551) ($2\theta = 43.6^\circ$), which are critical for distinguishing between the two structures [11,15,23]. Thus, it can be confirmed that the $Y_2Zr_2O_7$ synthesized in this experiment has a defect fluorite structure. Based on the XRD patterns, it can be concluded that pure $Y_2Zr_2O_7$ NPs with high crystallinity can be synthesized at a temperature of 600 °C when CA is introduced. Besides, the average crystallite size D of the CY0.2, CY0.4, CY0.8, CY1.2, and CY1.6 samples can be estimated by Scherrer equation: $D = K\lambda/(\beta\cos\theta)$, where θ is the Bragg angle (o), λ is the X-ray wavelength equal to 0.15406 nm, β is the FWHM of the diffraction peak, and K is the constant equal to 0.89.

The results showed that the average crystallite size of the CY0.2, CY0.4, CY0.8, CY1.2, and CY1.6 is 4.1 nm, 3.9 nm, 4.7 nm, 4.0 nm, and 4.2 nm, respectively. However, the intensity of the diffraction peaks in the XRD patterns does not show a significant variation with different amounts of CA. Thus, further analysis is required to assess the impact of CA amount on the as-prepared $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs.

The SEM images of $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different doping content of CA is shown in Figure 2b–f. It can be seen from Figure 2b, the CY0.2 powder exhibits irregularly shaped large particles with smooth surfaces and sizes exceeding 500 nm. As the amount of CA increases, the surface gradually develops a porous structure, with the pore size increasing alongside the CA amounts. Notably, as shown in Figure 2d, the morphology of CY0.8 powder reveals the highest number of pores, with the most uniform particle sizes, ranging in the tens of nanometers, and the least noticeable agglomeration between particles. Additionally, it can be observed that the large particles in all samples are likely composed of smaller, finer particles aggregated together.

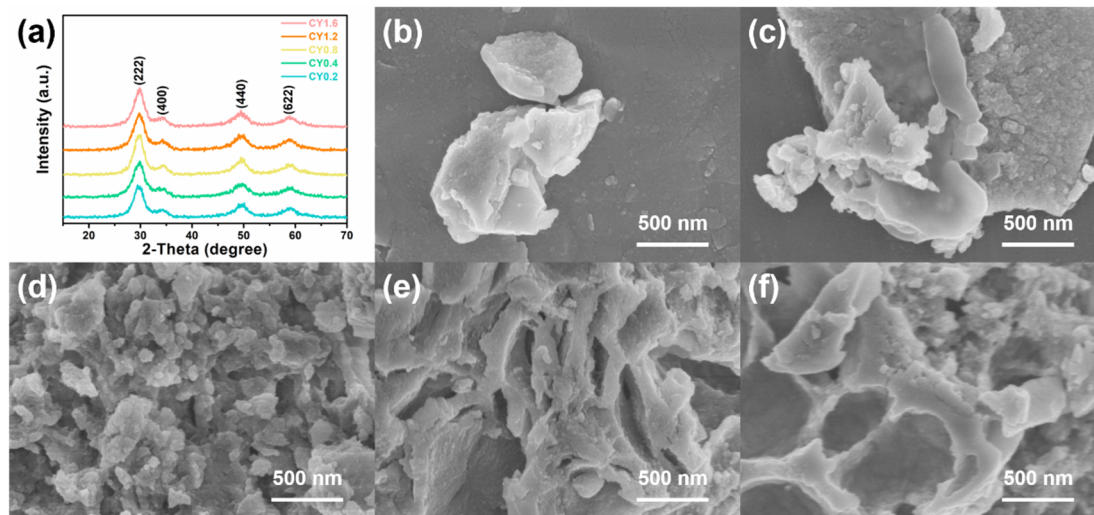


Figure 2. (a) XRD patterns; and SEM images of (b) CY0.2; (c) CY0.4; (d) CY0.8; (e) CY1.2; (f) CY1.6.

TEM analysis was used to further investigate the morphology of the as-prepared $\text{Y}_2\text{Zr}_2\text{O}_7$. The TEM images of Figure 3 show a stacked small size NPs morphology of $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different CA additions. As can be seen from Figure 3a–c, the compactness of the stacking between $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs is weakening and the dispersion is gradually increasing with the increase of CA introduction. There are stacking holes of uniform size between the CY0.8 NPs in Figure 3c. As can be seen from Figure 3d–e, further increase in CA additions, the degree of stacking between the NPs starts to increase again and the number of stacking holes is decreasing. Comparing CY0.8 with CY1.6, it can be clearly observed that the agglomeration between the NPs becomes larger again with the increase in CA addition and the number of stacking holes formed between the NPs decreases significantly. Figure 3f shows the HRTEM image of CY0.8 in the red dashed part of Figure 3c, which shows clear lattice stripes, indicating that the prepared CY0.8 NPs have a high degree of crystallinity. The approximate outline of the CY0.8 NPs is circled by the dashed line in the image, which proves that the size distribution of NPs is between 5 to 10 nm, the observation results are generally consistent with the calculated average crystallite sizes from XRD analysis. And the lattice fringes of 0.298 nm and 0.259 nm can correspond to the (222) and (400) crystal planes of $\text{Y}_2\text{Zr}_2\text{O}_7$ [6].

Figure 4a show the UV-vis diffuse reflectance spectra of the $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different doping content of CA. It can be seen that all $\text{Y}_2\text{Zr}_2\text{O}_7$ powders have strong absorption of UV light, in which the absorption edges of the CY0.2, CY0.4, CY0.8, CY1.2 and CY1.6 are 404 nm, 265 nm, 255 nm, 261 nm and 275 nm, respectively. This is because when the size of the prepared nanoparticles is less than 10 nm, they have an obvious quantum size effect, and the smaller the particle size, the wider the band gap [24]. As for CY0.2, the steep increase in the absorption edge is due to the addition of too little CA, exhibits severe aggregation and less associated with quantum confinement. As for CY0.4, CY0.8, CY1.2 and CY1.6, the optical differences are also associated with the combined effects of nanoparticle dispersion, crystallinity, and surface/interface structure. Therefore, the CY0.8 sample possesses the smallest absorption edges might attributed to the most uniformly dispersed nanoparticles, crystallinity among other samples.

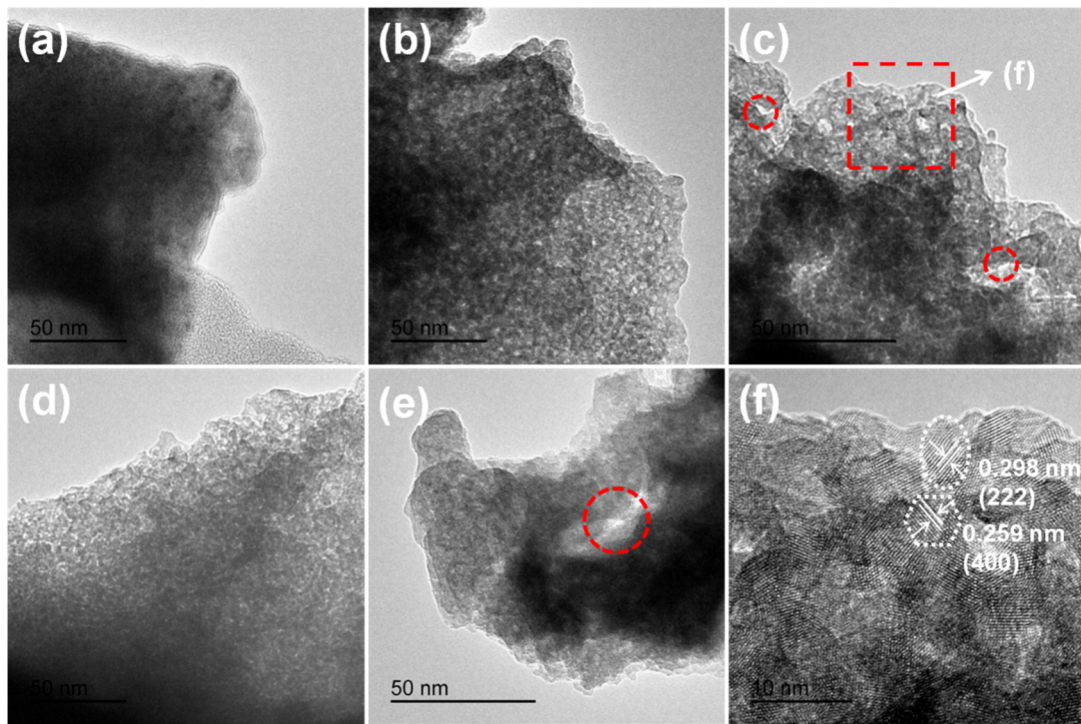


Figure 3. TEM images of $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different doping content of CA. (a) CY0.2; (b) CY0.4; (c) CY0.8; (d) CY1.2; (e) CY1.6; (f) HRTEM of CY0.8 (the enlarged view of the red dashed part in Figure 3c).

The PL spectra reflect the photogenerated electron-hole pairs complex luminescence and the lower fluorescence emission intensity reflects the lower recombination rate of the electron-hole pairs [25–27]. The PL spectra of $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different doping content of CA are shown in Figure 4b, the excited wavelength is at 351 nm. It can be seen that the prepared $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs have strong emission peaks mainly at ~590 nm, and the CY0.8 exhibits the lowest emission peak intensity, which may have higher photocatalytic activity. Although the emission peak intensity of CY0.2 is close to that of CY0.8, due to the severe agglomeration, reduced accessible active sites and hindered charge transport, the photocatalytic performance may be hindered. The CY1.2 has the strongest emission peak at ~590 nm, indicating that this material has the highest recombination rate of the electron-hole pairs under light excitation, and may be more suitable for fluorescent materials [28].

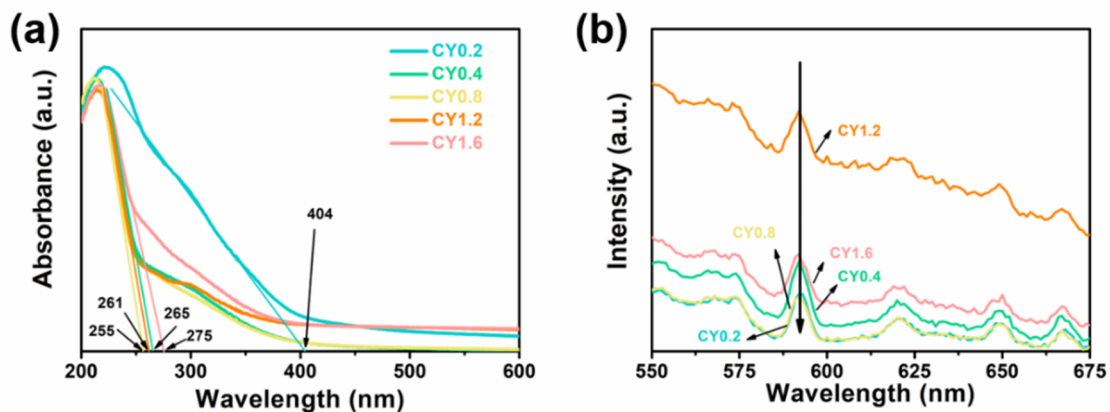


Figure 4. (a) UV-vis diffusion reflectance spectra, and (b) PL spectra of $\text{Y}_2\text{Zr}_2\text{O}_7$ prepared with different doping content of CA.

Based on the results of the photo adsorption experiment, the photocatalytic degradation of 10 mg/L Rh B solutions over $\text{Y}_2\text{Zr}_2\text{O}_7$ was carried out under UV light irradiation. As shown in Figure 5a, the photocatalytic degradation curves of Rh B by using different $\text{Y}_2\text{Zr}_2\text{O}_7$ samples are presented. The most intense absorption peak of Rh B at 553 nm was used as a reference, with a Rh B solution without any catalyst added serving as a blank. Under irradiation of 500 W Hg lamp, the photocatalytic performance of $\text{Y}_2\text{Zr}_2\text{O}_7$ synthesized with different amounts of CA follows the order of $\text{CY0.8} > \text{CY0.4} > \text{CY1.2} > \text{CY0.2} > \text{CY1.6}$. The CY0.8 powder exhibited the

highest photocatalytic efficiency, achieving a degradation rate of 97% after 80 min of exposure. This suggests that both insufficient and excessive CA addition are detrimental to the photocatalytic performance of the synthesized $\text{Y}_2\text{Zr}_2\text{O}_7$. When the CA addition is too low, the resulting sample exhibits tightly packed particles, severe agglomeration, and large particle sizes, all of which are unfavorable for photocatalytic performance. Conversely, when the CA addition is too high, the sample forms large pores that exert significant pressure on the $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs, hindering their dispersion and thereby reducing the photocatalytic activity of the synthesized $\text{Y}_2\text{Zr}_2\text{O}_7$. As shown in Figure 5b, the strongest absorption peak of CY0.8 was significantly flattened after 80 min of UV irradiation, indicating that Rh B in the solution was almost completely decomposed. In addition, the absorption peak was left-shifted to a shorter wavelength, from the initial 553 nm to 524 nm, suggesting that the process involved is the degradation of Rh B rather than adsorption [29].

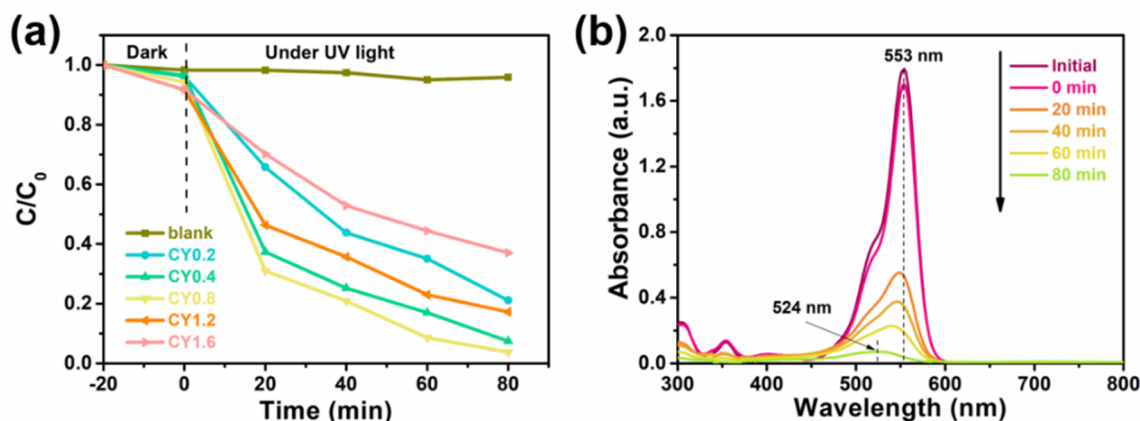


Figure 5. (a) Photocatalytic degradation of Rh B by different samples at irradiation of 500 W Hg lamp; (b) UV-vis spectra of Rh B at different irradiation time with the addition of CY0.8 photocatalyst.

$\text{Y}_2\text{Zr}_2\text{O}_7$ is described as a wide bandgap semiconductor with the valence band mainly derived from O 2p orbitals and the conduction band dominated by Zr 4d states. After the introduction of oxygen vacancies, localized defect states can form within the bandgap, which act as carrier trapping centers to facilitate charge separation and suppress electron-hole recombination. The UV-vis spectra indicate that variations in CA content affect the optical absorption behavior through changes in nanoparticle size and defect structure, while the PL results demonstrate significant differences in carrier recombination efficiency among the samples. In particular, the CY0.8 sample exhibits the lowest PL emission intensity, indicating the most effective suppression of electron-hole recombination, which is consistent with its superior photocatalytic activity. These results collectively support the conclusion that optimized defect concentration and electronic structure regulation play key roles in enhancing the photocatalytic performance of $\text{Y}_2\text{Zr}_2\text{O}_7$.

4. Conclusions

In conclusion, $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs with defect fluorite structure were successfully synthesized by citrate-gel-combustion method at the low-temperature of 600 °C, and the effects of the amount of CA on its morphology and the photocatalytic degradation of Rh B under UV light irradiation were investigated. Porous $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs can be easily and economically prepared by CA combustion, and the corresponding photocatalytic properties of the materials can be improved by adjusting the CA content. The $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs exhibit photo-absorption mainly in the UV light region. The results showed that the optimal photocatalysts were $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs prepared with a molar ratio of CA:Y = 0.8:1 (CY0.8). The CY0.8 NPs have the best photocatalytic activity due to its smaller particle size, better dispersion, and larger surface area. Thus, the CY0.8 NPs achieved a degradation efficiency of up to 97% after 80 min of UV light irradiation. The advantages of this protocol are as follows: (1) the reaction is a non-explosive redox exothermic process, where combustion generates a significant amount of heat and releases gases, which promotes the formation of $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs with high specific surface area at low temperature; (2) the preparation of the precursor is performed in solution, which ensures precise stoichiometry and homogeneity among the reactants. The resulting material features fine particle sizes with uniform distribution and minimal agglomeration; (3) during combustion of the xerogel, the C=O functional groups in the CA act as reducing agents, reducing nitrate ions of the reactants. This work provides a large-scale fabrication strategy of advanced porous metal oxide nanomaterials for photocatalytic applications.

Future studies will focus on improving phase and morphology control of $\text{Y}_2\text{Zr}_2\text{O}_7$ NPs, including particle size, distribution, porosity, and agglomeration behavior. Particular attention will be given to the sensitivity of the fuel-to-oxidant ratio, precursor stability, and their effects on microstructure evolution and reproducibility. In addition, the cost-performance ratio, energy consumption, and long-term cycling stability of the photocatalysts will be systematically evaluated to assess their potential for large-scale environmental applications.

Author Contributions

Y.L. (Yijia Luo): writing—original draft, methodology, investigation, formal analysis, data curation, conceptualization, funding acquisition; L.C.: writing—review & editing, funding acquisition, supervision; Y.F.: visualization, investigation; Y.Z.: methodology, formal analysis; Y.L. (Yijun Liu): data curation, investigation; J.H.: writing—review & editing, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available from the corresponding author on request.

Conflicts of Interest

Yong Zhao and Yijun Liu are employees of Guangdong Mona Lisa Group Co. Ltd. Their employment did not influence the design, execution, interpretation, or reporting of the study. All other authors declare no competing interests.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used DeepL to polish English grammar. All ideas, experimental data, analysis and conclusions in this paper are independently completed by the authors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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