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Synthesis of g-C₃N₄/TiO₂ nanostructures for enhanced photocatalytic reduction of U(vi) in water

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Photocatalytic technology is a valid solution for the remediation of wastewater containing uranium. In this study, the synthesis of Z-scheme g-C₃N₄/TiO₂ catalysts was made by a thermal synthetic approach for photocatalytic U(vi) reduction. The characterization results revealed the successful synthesis of g-C₃N₄/TiO₂ nanostructures. The g-C₃N₄ surface was uniformly coated with TiO₂ nanoparticles. The depletion of U(vi) in water evaluated the photocatalytic activity of g-C₃N₄/TiO₂ under UV light irradiation. The photocatalytic tests showed that g-C₃N₄/TiO₂ exhibited more effective photocatalytic activity than the raw materials (1.64 and 56.97 times higher than TiO₂(P25) and g-C₃N₄, respectively). Besides, a pseudo-first-order model was followed by the experimental kinetic data for the photocatalytic process. Moreover, g-C₃N₄/TiO₂ still presented high photocatalytic activity after four reacting cycles. Based on these experiment results, the improved photocatalytic activity could be attributed to the Z-scheme mechanism, which decreased the recombination of photo-produced electrons and holes. The synthesis of these g-C₃N₄/TiO₂ nanomaterials provides a facile and inexpensive method for treating wastewater containing U(vi).

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1. Introduction

As nuclear energy develops, uranium increasingly has entered the water environment, which seriously threatens human health.¹ Therefore, the treatment of wastewater containing uranium has become a research focus. The primary idea to solve this problem is to convert soluble U(vi) into insoluble U(IV) to separate it from the water.² Under light illumination, photocatalysts can produce electrons and holes for redox reactions. It has been proven to be an effective approach of treating wastewater containing U(vi). Compared with traditional treatment methods, photocatalysis has the advantages of simple operation, low energy consumption and no secondary pollution.³

The photocatalyst is the main point in a photocatalytic reaction process. As the most classic photocatalyst, TiO₂ has attracted the attention of researchers for its high activity and stability.⁴ TiO₂ commodity P25 is the only photocatalyst used in commercials currently. However, the poor visible light responsiveness limits its further applications.^{5,6} Recently, various new photocatalysts have been developed such as graphitic carbon nitride (g-C₃N₄), iron oxide (α-Fe₃O₄), ZnO and noble metals.^{7–12}

Among them, g-C₃N₄ has been a new focus issue in the photocatalytic field because of its narrow bandgap, which can increase the range of light absorption. Moreover, researchers have tried to improve the photocatalytic performance by modifying the photocatalysts. At present, there are three main modification methods for catalysts, such as morphology control, element doping and a variety of materials for composites.^{13,14} Among these modification methods, composite materials could avoid many disadvantages and limitations of a single semiconductor in a photocatalytic process. In many mechanisms of composite, the Z-scheme photocatalytic mechanism was proposed on a composite, whereby the photo-produced electrons (with less potential energy) of a semiconductor photocatalyst and the holes (with less potential energy) of another semiconductor were recombined through an interface connection, thus leaving the photo-produced electrons with higher potential energy and holes on their respective semiconductors to form active sites.^{15,16} It could efficiently separate photo-produced electrons and holes, thereby inhibiting their recombination.^{17,18} According to an authoritative report, there are no more than 40 studies about the photocatalytic reduction of U(vi).¹⁹ Among these reports are even fewer reports on the application of Z-scheme photocatalyst to reduce U(vi).^{20–23} However, there have been numerous reports about the application of Z-scheme photocatalysts to remove other pollutants in water.^{24,25} Therefore, the research on the application of Z-scheme photocatalysts for photocatalytic reduction of U(vi) is innovative. Moreover, the research on the mechanism of U(vi) reduction by the Z-scheme photocatalyst would help increase photocatalytic efficiency.

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In this paper, $g\text{-C}_3\text{N}_4/\text{TiO}_2$ composites were presented for photocatalytic $\text{U}(\text{vi})$ reduction application. TiO_2 (P25) nanoparticles were coated on $g\text{-C}_3\text{N}_4$ to form a Z-scheme photocatalyst by a thermal synthetic method. The morphology and structure characterizations were presented subsequently. $\text{U}(\text{vi})$ reduction in aqueous was employed for evaluating the photocatalytic activities of this $g\text{-C}_3\text{N}_4/\text{TiO}_2$. Moreover, the Z-scheme photocatalytic mechanism of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ was investigated, which could decrease the recombination of photo-produced electrons and holes.

2. Experimental

2.1 Preparation of material

Chemical reagents applied in this research were all at analytical grade without further purification. All the reagents were domestic. The TiO_2 particle used in this study was P25, which was purchased from King Chemical. Standard $\text{U}(\text{vi})$ solution was prepared by dissolving U_3O_8 (99%) with HCl and H_2O_2 under heating conditions. The porcelain crucible containing some urea was placed in a muffle furnace, and the temperature was raised from room temperature to 600°C for 2 h, and then cooled down naturally. The ceramic crucible was removed, and its content was grounded into powder to obtain the yellow $g\text{-C}_3\text{N}_4$ photocatalyst. A certain amount of TiO_2 and $g\text{-C}_3\text{N}_4$ were placed into three beakers. The surface-mass ratio of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ was maintained at 1 : 1, 2 : 1 and 3 : 1, marked as $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$, $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-2}$ and $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-3}$, respectively. The raw materials were then added into deionized water, stirred evenly, and ultrasonic mixed for 15 min until the powder had completely dispersed. The suspension was transferred into a ceramic crucible and heated to powder form at 80°C for 5 h. Then, the ceramic crucible was calcined at 400°C for 2 h in a muffle furnace. After being cooled to indoor temperature, the ceramic

crucible was removed and its content grounded into powder to obtain the composite photocatalyst.

2.2 Characterization

The characterization was performed on the $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$ sample. X-ray diffraction (XRD) characterized the crystal structure of the photocatalyst by applying a D/MAX-RB diffractometer (Bruker, D8 advance, Germany) and adopting $\text{Cu K}\alpha$ radiation (ranging from 5° to 95° , Step length: 0.01° , each step 0.1 s). Scan electron microscopy (SEM), which was tested by a SUPRATM55 high-resolution field emission scanning electron microscope (operating voltage of 2 kV, standard aperture diaphragm of $30\ \mu\text{m}$, SE2 secondary electron detector imaging) (Zeiss, Germany), analyzed the surface morphology of the photocatalyst. X-ray photoelectron spectroscopy (XPS, Thermo Scientific, Escalab 250Xi, UK) was used to perform the surface elemental analysis of the photocatalyst by applying an ESCALAB II XPS system. UV-vis Diffuse Reflectance Spectra (DRS) was examined to obtain the optical absorption property of the photocatalyst (Shimadzu, UV-3600, Japan, equipped with an integrating sphere). The specific surface area was calculated by the Brunauer–Emmett–Teller (BET) method (Micromeritics ASAP 2460 instrument at 77 K with N_2 as absorbate). A Xe lamp, as an excitation source, was used to record the PL spectra on a fluorescence spectrophotometer (FS5, Edinburgh Instruments Ltd., UK).

2.3 Photocatalytic activities of photocatalysts

The photocatalytic reduction of $\text{U}(\text{vi})$ solution evaluated the photocatalytic activities of the photocatalysts prepared. In the photocatalytic process, 0.02 g of as-prepared photocatalysts was added into 50 mL of $\text{U}(\text{vi})$ solution (initial concentration of $10\ \text{mg L}^{-1}$). Moreover, 2 mL of methanol was added into the

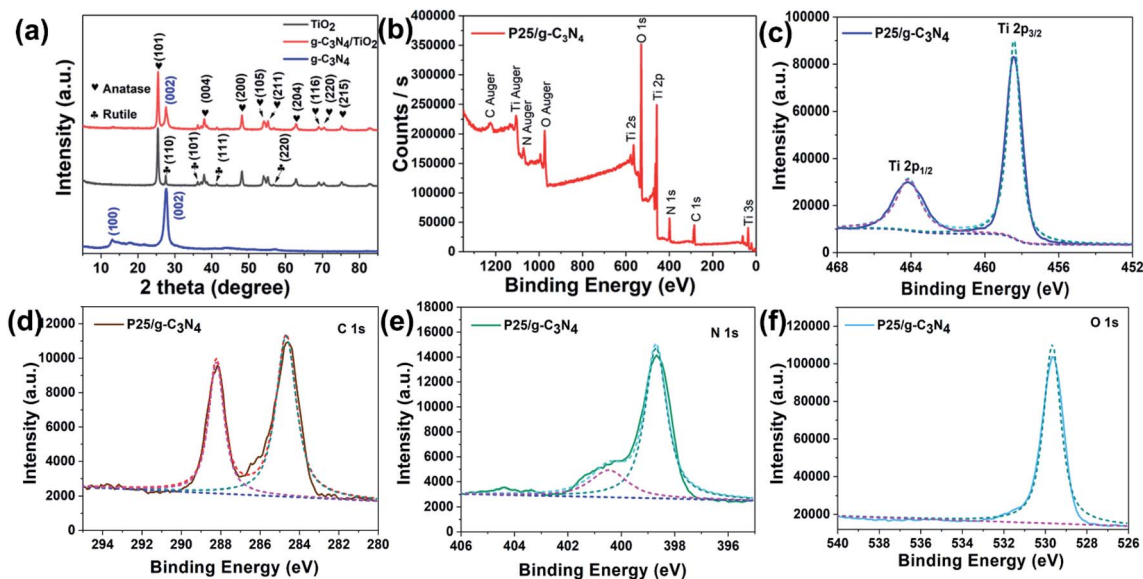


Fig. 1 (a) XRD patterns of $g\text{-C}_3\text{N}_4$, TiO_2 and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ prepared, the labels of ♥ and ♣ are the corresponding peaks of anatase TiO_2 and rutile TiO_2 , respectively; (b) the complete XPS spectra of $g\text{-C}_3\text{N}_4/\text{TiO}_2$, main peaks of Ti 2p (c), C 1s (d), N 1s (e) and O 1s (f) for $g\text{-C}_3\text{N}_4/\text{TiO}_2$.

suspension, which was used as the hole scavenger in the reaction. The mixture was ultrasonic oscillated for 30 min to disperse the photocatalysts. The pH of the suspension was adjusted to about 5.0 by hydrochloric acid and sodium hydroxide. For the elimination of the dissolved oxygen and realization of the adsorption–desorption equilibrium under anaerobic conditions, the suspension was bubbled with nitrogen (99.99%) for 30 min in the dark. Then, the mixture was illuminated by an ultraviolet light of 500 W. The photocatalytic process was carried out in the photocatalytic apparatus (GG-GHX-V, Shanghai Guigo Industrial Co. Ltd). Arsenazo III Spectrophotometric Method, used after centrifugation at regular intervals, determined the $U_{(VI)}$ concentration of the mixture. The following expression was used to calculate the removal ratios ($R_{U(VI)}$) of $U_{(VI)}$:

$$R_{U(VI)} = 1 - C_t/C_0 = (A_0 - A_t)/A_0 \times 100\%$$

where $R_{U(VI)}$ is the removal ratios of $U_{(VI)}$; C_t and C_0 are the concentration of $U_{(VI)}$ at 0 and t time; and A_0 and A_t are the absorbance intensity corresponding to 0 and t time, respectively. The stability of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ was assessed by reusing the photocatalyst in four repeated tests for the decrease of $U_{(VI)}$ under the same conditions.

3. Results and discussion

3.1 Structural characterization of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures

The characterization of the as-obtained $g\text{-C}_3\text{N}_4$, TiO_2 (P25) and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures were made by XRD and XPS techniques. The XRD patterns for these nanostructures are presented in Fig. 1a. In the XRD pattern of pure $g\text{-C}_3\text{N}_4$ (blue line), the significant diffraction peaks appeared at positions of 13.1° and 27.3° , and are indexed to (100) and (002) planes of $g\text{-C}_3\text{N}_4$. These are attributed to the planar, which repeats cell structure and sandwich stack reflection of $g\text{-C}_3\text{N}_4$.^{26,27} The average interlayer distances were 0.675 nm and 0.326 nm, respectively, calculated by the Scherrer equation. After compositing with TiO_2 (P25), the significant peaks of $g\text{-C}_3\text{N}_4$ still had decreased peak intensity. The apparent diffraction peaks of anatase TiO_2 and rutile TiO_2 are shown in the $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures (red line), where most of these peaks displayed (101), (004), (200), (105), (211), (204), (116), (220) and (215) planes of anatase TiO_2 ,²⁸ while other peaks were attributed to (110), (101), (111) and (220) planes of rutile TiO_2 . These peaks are according to the XRD results of pure P25 (black line).

Moreover, Fig. 1b–f show the XPS spectra of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures. In Fig. 1b, the full XPS spectrum presented all

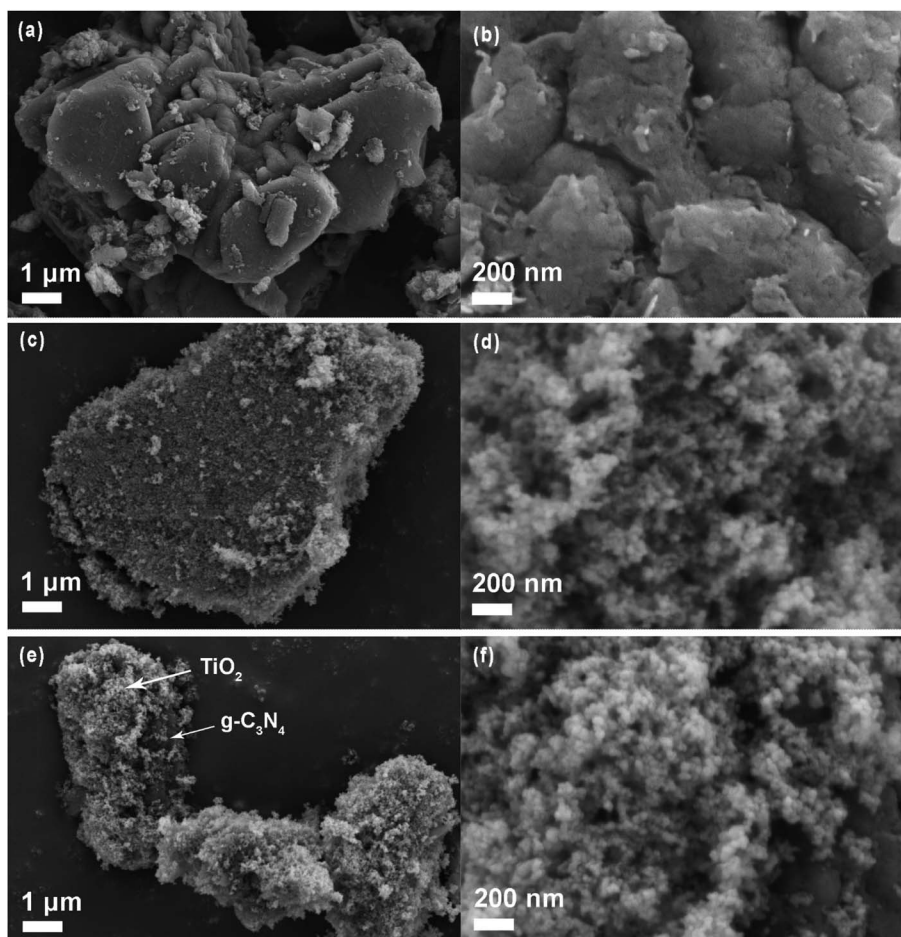


Fig. 2 SEM images of pure $g\text{-C}_3\text{N}_4$ (a and b), TiO_2 (P25, c and d) and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures (e and f).



the peaks (C 1s, N 1s, Ti 2p, O 1s) of g-C₃N₄ plus TiO₂ nano-materials. Fig. 1c–f showed high-resolution XPS spectra of Ti 2p, C 1s, N 1s and O 1s. After employing the XPS-peak-differentiation-imitating analysis method, Ti 2p_{1/2} and Ti 2p_{3/2} peaks appeared in Fig. 1c. C 1s and N 1s further confirmed the successful synthesis of g-C₃N₄ (Fig. 1d and e). The two C 1s that peaked at 284.8 and 288.0 eV, respectively, were caused by an aromatic carbon atom and C–N–C coordination (Fig. 1d). The O 1s identified that the TiO₂ existed in these nanostructures (Fig. 1f). Thus, the generation of g-C₃N₄/TiO₂ nanostructures can be confirmed by these structural characterizations.

3.2 Morphology of g-C₃N₄/TiO₂ nanostructures

The SEM images of as-synthesized pure g-C₃N₄, TiO₂ (P25) and g-C₃N₄/TiO₂ nanostructures are presented in Fig. 2. The g-C₃N₄ polymer with a blocky structure was gathered by many irregularly shaped wrinkled sheets, as displayed in Fig. 2a. These blocky structures with holes of g-C₃N₄ polymers could be reported as per the magnified SEM image of g-C₃N₄ (Fig. 2b). These holes may give the g-C₃N₄ many active reaction sites for various applications. The SEM images of the pure TiO₂ (P25) are shown in Fig. 2c and d. As shown in these images, the particle size of TiO₂ (P25) was too small (less than 100 nm) compared with g-C₃N₄. It was more favorable for TiO₂ to disperse on the

surface of g-C₃N₄. After compositing TiO₂ with g-C₃N₄, TiO₂ nanoparticles uniformly adhered to g-C₃N₄ (Fig. 2e and f). This combination could promote the charge transfer between g-C₃N₄ and TiO₂ by the Z-scheme route. However, as presented in Fig. 2e, there still certain parts of g-C₃N₄ that were uncovered due to the imprecise control of the hydrothermal method. This result further displays the successful synthesis of the g-C₃N₄/TiO₂ nanostructures.

3.3 Surface area of g-C₃N₄/TiO₂ nanostructures

Adsorption and desorption experiments by N₂ were carried out at 77 K, and N₂ isotherms have been applied to calculate the specific surface area by the multi-point BET method. As shown in Fig. 3a, the shape of the isotherm with two capillary condensation steps is like a type IV isotherm according to the IUPAC classification, indicating the presence of mesopores. The shape of the hysteresis loop was of the type H3, and the hysteresis loop shifts at high relative pressures (P/P_0) between 0.8 and 1.0, which suggests a mesoporous structure. Mesoporosity is typical of wrinkled, sheet-like particles, and this result is consistent with SEM images. This mesopore size distribution was confirmed by the pore size distributions shown in the inset in Fig. 3a. The average pore diameter of g-C₃N₄/TiO₂ nanostructures is estimated as 37 Å, which suggests the

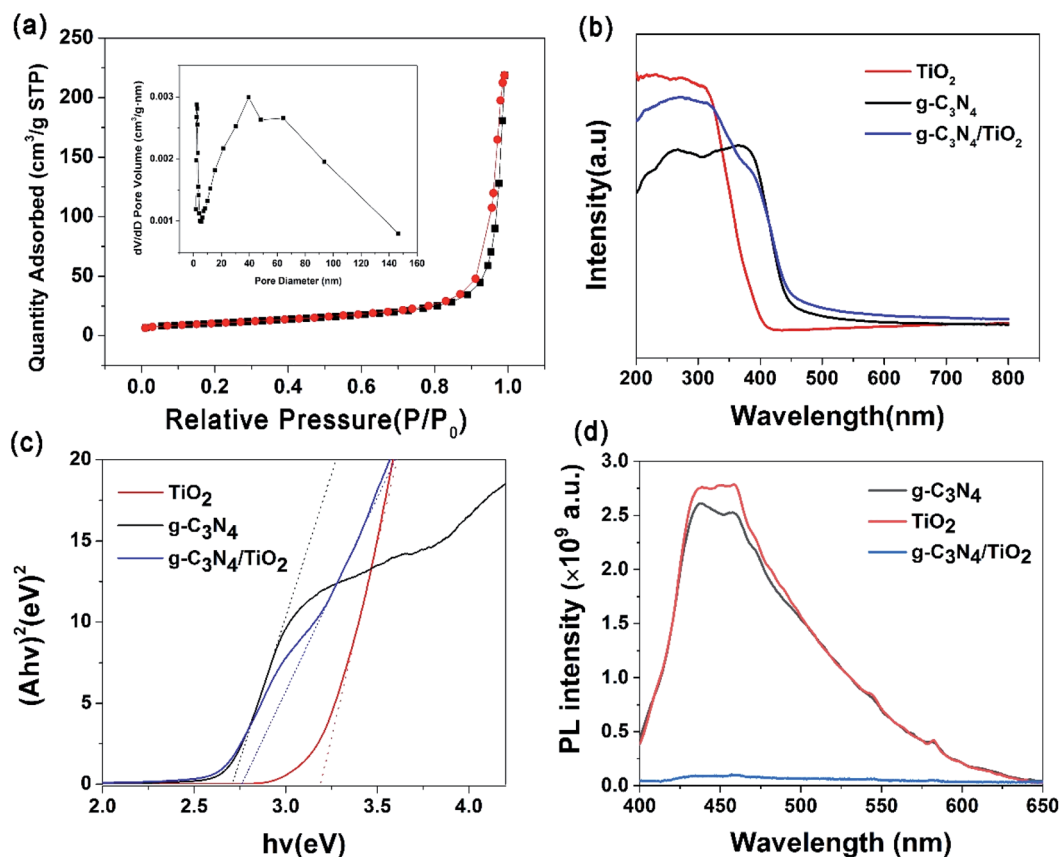


Fig. 3 (a) N₂ adsorption–desorption isotherm of g-C₃N₄/TiO₂ nanostructures. Inset: pore size distribution of g-C₃N₄/TiO₂ nanostructures; (b) UV-vis diffuse reflectance spectra of pure g-C₃N₄, TiO₂ (P25) and g-C₃N₄/TiO₂ nanostructures; (c) plots of the $(Ah\nu)^2$ versus $(h\nu)$ for pure g-C₃N₄, TiO₂ (P25) and g-C₃N₄/TiO₂ nanostructures, (d) PL spectra of g-C₃N₄, TiO₂ (P25) and g-C₃N₄/TiO₂ nanostructures.

existence of mesopores. The BET specific area of the $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures was $36.2\text{ m}^2\text{ g}^{-1}$, which is between $g\text{-C}_3\text{N}_4$ ($29.4\text{ m}^2\text{ g}^{-1}$) and TiO_2 ($51.6\text{ m}^2\text{ g}^{-1}$).

3.4 Optical properties of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures

Firstly, UV-vis diffuse reflectance spectroscopy (DRS) was used to investigate the optical properties of pure $g\text{-C}_3\text{N}_4$, TiO_2 (P25) and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures. As shown in Fig. 3b, the significant absorption peak of $g\text{-C}_3\text{N}_4$ was at $\sim 398\text{ nm}$, the absorption end of $g\text{-C}_3\text{N}_4$ was $\sim 450\text{ nm}$ (black line). The pure TiO_2 (P25) showed a high UV-light absorption, and the absorption edge was $\sim 400\text{ nm}$ (red line). After compositing TiO_2 with $g\text{-C}_3\text{N}_4$, the absorption edge was located on the range between 400 and 450 nm , and the absorption intensity in the UV region was lower than pure TiO_2 but higher than $g\text{-C}_3\text{N}_4$ (blue line), which reveals a successful synthesis of the $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures. According to the plot of $(Ah\nu)^2$ versus $(h\nu)$, as shown in Fig. 3c, the bandgap energies (E_g) of pure $g\text{-C}_3\text{N}_4$, TiO_2 (P25) and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ have been estimated to be 2.7 eV , 3.2 eV and 2.75 eV , respectively. The calculation results show that the bandgap width of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures was very close to that of $g\text{-C}_3\text{N}_4$, which is narrower than that of TiO_2 (P25).

PL spectra were the principal approach to test the efficiency of charge separation during the photocatalytic process.¹⁶ The release of energy in the form of PL emission was made while recombining electron-hole pairs. Therefore, greater PL

intensity shows a greater recombination rate of charge carriers. Hence, the PL spectra of pure $g\text{-C}_3\text{N}_4$, TiO_2 (P25) and $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures were performed in Fig. 3d. For pure $g\text{-C}_3\text{N}_4$ and TiO_2 (P25), there is a relatively strong emission peak at $\sim 452\text{ nm}$, which is displayed in the PL spectra (black line and red line), indicating that there are many photo-produced electrons combined with holes. A large amount of energy is released, which is detected by the PL spectra. For $g\text{-C}_3\text{N}_4/\text{TiO}_2$, there is no prominent emission peak in PL spectra (blue line). This phenomenon indicates the decreased recombination efficiency of photo-produced electrons and holes, which enhanced the photocatalytic performance of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ because of its Z-scheme structure.²⁹

3.5 Photocatalytic reduction of U(VI)

U(VI) reduction was used to evaluate the photocatalytic activity of the photocatalysts. Fig. 4a and b show the results. Without photocatalysts, there is no obvious change of U(VI) concentration, showing U(VI) stability under light and negligible self-photocatalysis process. Under the condition of adding photocatalyst, the U(VI) concentration reduces slightly after the dark reaction reaches adsorption equilibrium in the first 30 min. It is indicated that photocatalyst has a certain adsorption ability for U(VI) . For pure $g\text{-C}_3\text{N}_4$, U(VI) concentration does not decline obviously after the light is turned on, which shows that the photocatalytic effect of pure $g\text{-C}_3\text{N}_4$ for U(VI) is greatly restricted.

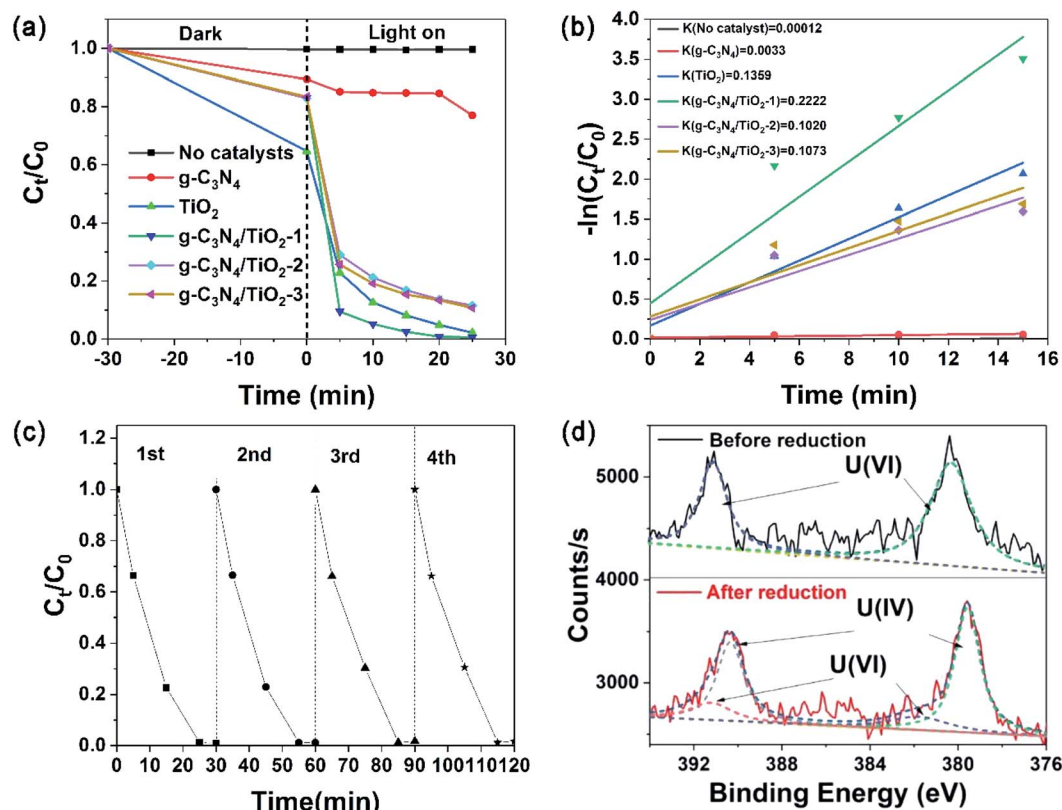


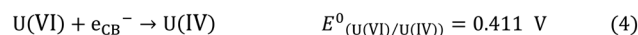
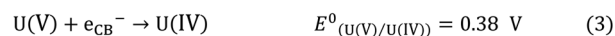
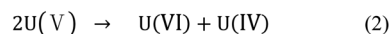
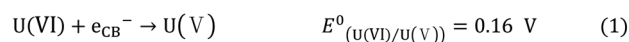
Fig. 4 (a) The variation of U(VI) during the reaction; (b) the rate constant (k) of U(VI) reduction; (c) cycling runs in the photocatalytic reduction of U(VI) ; (d) XPS spectrum of U 4f for the U element on the surface of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ before (top) and after (bottom) reduction process.



For TiO_2 , $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$, $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-2}$ and $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-3}$, the $U(\text{vi})$ concentration drop rapidly in the first 5 min after the light is turned on. The $U(\text{vi})$ concentration decreases gradually in the following 20 min. As the most active photocatalyst, $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$ removed >99% of $U(\text{vi})$ after illumination for 25 min. The reaction kinetics for the removal of $U(\text{vi})$ quantitatively was researched by pseudo-first-order kinetics model. As expressed in the formula $-\ln(C_0/C_t) = kt$, where k stands for the apparent reaction rate constant, C_0 and C_t are the concentrations of aqueous $U(\text{vi})$ at reaction time t_0 and t , respectively. As displayed in Fig. 4b, the apparent rate constants k for $g\text{-C}_3\text{N}_4$, TiO_2 , $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$, $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-2}$ and $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-3}$ were calculated to be 0.0033, 0.1359, 0.2222, 0.1020 and 0.1073 min^{-1} , respectively. As the maximum in the series photocatalysts, the k values of $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$ was 1.64 times of TiO_2 (the maximum of raw material), indicating that the photocatalytic performance has been significantly improved through the material composite.

The long-time stability of a photocatalyst during the photocatalytic reaction is significant for practical use. Fig. 4c shows the recycling usability of four times for $g\text{-C}_3\text{N}_4/\text{TiO}_2\text{-1}$ in the photocatalytic process. After each cycle, centrifugation collected and separated the photocatalysts from the suspension aqueous. Photocatalysts were ultrasonic oscillated to peel off surface sediments and then washed by deionized water. Subsequently, the drying of photocatalysts was carried out at 60 °C before the next recycle. As shown in Fig. 4c, the curves for each cycle were very similar. The final removal rate of every cycle was more than 99%, which indicates the stable photocatalytic activity of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ after several recycles.

XPS spectra of U element on $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures were performed for verification of the reduction process. Fig. 4d shows higher resolution XPS spectra of U 4f (after and pre-reduction). After the reduction of $U(\text{vi})$ into $U(\text{iv})$, the peak positions of U 4f_{5/2} and 4f_{7/2} were changed. In the bottom red curve, the peak-differentiating technique was used to obtain four peaks located at 379.6, 381.9, 390.4, and 391.3 eV. The two peaks at 381.9 and 391.3 eV originated from $U(\text{vi})$, these positions were matched well with that of $U(\text{vi})$ sample without reduction (up to black line), and peaks at 379.6 and 390.4 eV belong to $U(\text{iv})$. The above results showed that most of the $U(\text{vi})$ on the surface of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures were reduced into $U(\text{iv})$.³⁰



Scheme 1 Proposed mechanistic steps for $U(\text{vi})$ photocatalytic reduction.

3.6 Reduction mechanisms of $U(\text{vi})$

After the above results and discussion, Fig. 5 proposed the possible mechanism of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ photocatalytic reduction of $U(\text{vi})$. $g\text{-C}_3\text{N}_4$ and TiO_2 formed their photo-produced electrons and holes, respectively, in their internal parts under light irradiation. According to the relative position of VB and CB in $g\text{-C}_3\text{N}_4$ and TiO_2 , the photo-produced electrons produced by TiO_2 migrate to the interface of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ and integrate holes in the part of $g\text{-C}_3\text{N}_4$. The photo-produced electrons produced by $g\text{-C}_3\text{N}_4$ are used as a reduction site to reduce the $U(\text{vi})$ into $U(\text{iv})$. The holes in the VB of TiO_2 oxidize methanol into CO_2 and H_2O as oxidation sites. In this way, the photo-produced electrons and holes involved in the redox reaction are reacted on their respective semiconductors. The recombination of photo-produced electrons and holes is effectively avoided, increasing photocatalytic efficiency.³¹ At present, there are two mainstream opinions about the reduction process of $U(\text{vi})$.¹⁹ In the first opinion, the reduction process of $U(\text{vi})$ consists of two steps,³² which is shown as eqn (1)–(3) in Scheme 1. $U(\text{vi})$ is reduced to $U(\text{v})$ by photo-produced electrons in the first step (eqn (1)). $U(\text{v})$ can spontaneously react to $U(\text{vi})$ and $U(\text{iv})$ (eqn (2)), which follows the principle of electronic equilibrium. Moreover, $U(\text{v})$ can be further reduced to $U(\text{iv})$ by photo-produced electrons (eqn (3)). Another opinion indicated that $U(\text{vi})$ could be reduced to $U(\text{iv})$ directly just as eqn (4) in Scheme 1.³³ As displayed in Fig. 5, the reduction potential of CB on $g\text{-C}_3\text{N}_4$ ($E^0 = -1.3 \text{ eV}$) was more passive than the decreased potential for a series of reactions. Theoretically, the reduction reaction can proceed smoothly.

4. Conclusions

A thermal synthetic approach was proposed for the synthesis of Z-scheme catalyst $g\text{-C}_3\text{N}_4/\text{TiO}_2$. According to the results of characterization, a successful synthesis of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures was revealed. By comparing with raw materials, $g\text{-C}_3\text{N}_4/\text{TiO}_2$ displayed much greater photocatalytic activities for the reduction of radioactive $U(\text{vi})$ under the condition of UV light illumination (1.64 times higher of TiO_2 and 56.97 times of $g\text{-C}_3\text{N}_4$). More than 99% of $U(\text{vi})$ was removed by $g\text{-C}_3\text{N}_4/\text{TiO}_2$ after illumination for 25 min. XPS analyses showed that most of the $U(\text{vi})$ on the surface of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ were reduced into $U(\text{iv})$. After the reaction kinetics analysis, the photocatalytic reaction follows pseudo-first-order kinetics. Moreover, the $g\text{-C}_3\text{N}_4/\text{TiO}_2$ displayed good stability after four reused tests. Its Z-scheme

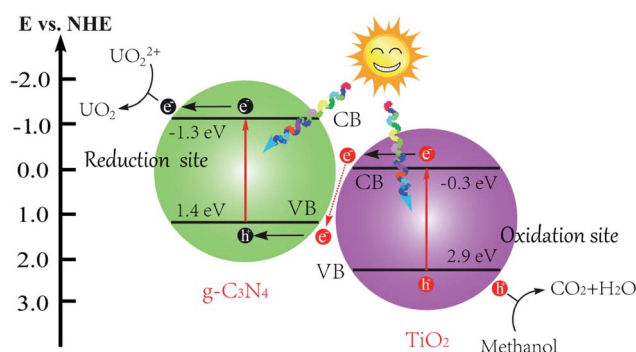


Fig. 5 The diagram of the proposed mechanism of $g\text{-C}_3\text{N}_4/\text{TiO}_2$ nanostructures under simulated sunlight irradiation.



structure, which decreased recombination efficiency of photo-produced electrons and holes, could cause the enhancement of the photocatalytic activities of g-C₃N₄/TiO₂. In summary, the g-C₃N₄/TiO₂ practically represent a suitable in U(VI) photocatalytic reduction.

Author contributions

Yuelin Liu contributed to the conception and design of the study. Shanshan Wu contributed to the acquisition of data. Yuelin Liu and Jun Liu contributed to the analysis and interpretation of data. Yuelin Liu contributed to drafting the manuscript. Shuibo Xie and Jun Liu contributed to revising it critically for important intellectual content. Shuibo Xie and Yingjiu Liu contributed to the reagents/materials/analysis tools.

Conflicts of interest

The authors declare no conflict of interest.

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