

# Enhanced removal of acid orange II from aqueous solution by V and N co-doping TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite photocatalyst induced by pulsed discharge plasma

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## ABSTRACT

This paper presents a study of V and N co-doping TiO<sub>2</sub> embedding multi-walled carbon nanotubes (MWCNTs) supported on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> pellet (V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>) composite photocatalyst induced by pulsed discharge plasma to enhance the removal of acid orange II (AO7) from aqueous solution. The photocatalytic activity of the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite to AO7 removal induced by the pulsed discharge plasma was evaluated. The results indicate that the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite possesses enhanced photocatalytic activity that facilitates the removal of AO7 compared with the TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composites. Almost 100% of AO7 is removed after 10 min under optimal conditions. The V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> photocatalyst exhibits the best removal effect for AO7. Analysis of the removal mechanism indicates that the enhancement of the removal of AO7 resulting from V and N co-doping causes TiO<sub>2</sub> lattice distortion and introduces a new impurity energy level, which not only reduces the band gap of TiO<sub>2</sub> but also inhibits the recombination of the e<sub>cb</sub><sup>-</sup>/h<sub>vb</sub><sup>+</sup> pairs.

**Key words** | azo dye, co-doping, pulsed discharge plasma, removal mechanism, TiO<sub>2</sub>-MWCNTs

## HIGHLIGHTS

- An efficient and easily recycled V/N-MWCNTs-TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite was prepared.
- Activity of the composite induced by discharge plasma to AO7 removal was evaluated.
- Synergistic effect of discharge plasma and catalyst effectively improve AO7 removal.
- The composite demonstrates adequate recycling performance in a discharge plasma system.
- Possible mechanisms of AO7 removal were analyzed.

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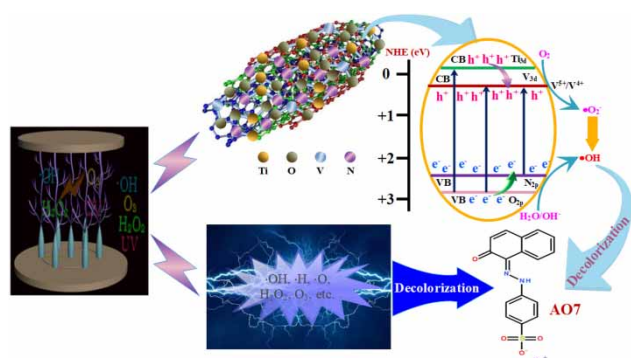
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## GRAPHICAL ABSTRACT

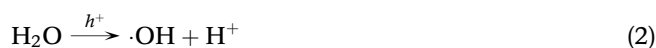


## INTRODUCTION

Pulsed discharge plasma technology has been widely studied as one of several advanced oxidation processes in the treatment of persistent liquid phase organic pollutants, specifically in the decolorization of textile dye wastewater (Jiang *et al.* 2014). It not only directly generates oxidizing species (such as  $\cdot\text{OH}$ ,  $\cdot\text{O}$ ,  $\text{H}_2\text{O}_2$  and  $\text{O}_3$ ) during the discharge process but also with physical effects, such as ultraviolet (UV) light, strong electric fields, electro-hydraulic cavitations and supercritical water oxidation, etc. (Joshi *et al.* 1995; Locke *et al.* 2006; Jiang *et al.* 2012). However, the physical properties, especially for light, are not fully utilized for the degradation of pollutants. If the physical effects that possess parts of the discharge energy could also be utilized for the degradation of pollutants, an enhancement of the removal rate of the pollutants and the utilization rate of the discharge energy could be realized.

$\text{TiO}_2$ , as a good photocatalytic material, has been extensively studied in the last two decades due to its potential as a low cost, non-toxic, highly efficient and stable photocatalyst under UV light irradiation (Murthy *et al.* 2017). Fujishima *et al.* (2000) indicated that even a few photons (i.e. as low as  $1 \mu\text{W}\cdot\text{cm}^{-2}$ ) can be sufficient to induce a reaction on the surface of the  $\text{TiO}_2$  photocatalyst. During the excitation process, a positively charged vacancy or hole ( $h^+$ ) can generate several active species, such as  $\cdot\text{OH}$  and  $\cdot\text{O}_2$ , to mineralize the pollutants in water. In addition, research has shown that the reaction rate increases linearly with increasing light intensity at relatively low light intensities ( $<25 \text{ mW}\cdot\text{cm}^{-2}$ ), but with the increase of light intensity, the incident photon-to-current efficiency decreased due to few delivered photons being converted into electrons and transported through the external electrical circuit (Herrmann 1999; Garcia-Segura *et al.* 2018).

Clearly, even though the UV intensity produced in the discharge is small (Zhang *et al.* 2013a), it can activate the  $\text{TiO}_2$  catalyst. Therefore, a nanosized  $\text{TiO}_2$  photocatalyst driven by discharge plasma is recognized as a potential technology, which has been applied to treat multifarious water contaminants. It is characterized by high energy utilization, excessive demineralization and less byproducts (Zhang *et al.* 2013b; Zhang *et al.* 2019). The main reaction mechanisms of the plasma catalyst system are shown as follows (Qin *et al.* 2009; He *et al.* 2014; Chang & Hu 2020):



In our previous work, multi-walled carbon nanotubes (MWCNTs) embedded with  $\text{TiO}_2$  supported on  $\gamma\text{-Al}_2\text{O}_3$  pellet ( $\text{TiO}_2\text{-MWCNTs}/\gamma\text{-Al}_2\text{O}_3$ ) composite photocatalysts were used to remove azo dye in a discharge plasma system

(Li *et al.* 2016). Although we obtained a high removal rate of azo dye after 60 min treatment, the TiO<sub>2</sub> still suffers from some drawbacks, such as low quantum efficiency, high recombination rate, large band gap (3.2 eV) and low activity (Hashimoto *et al.* 2005). Over the past decades, metal-doped TiO<sub>2</sub> photocatalysts have been widely studied for improved photocatalytic performance in the degradation of various organic pollutants. However, doping metal showed several disadvantages: thermal instability of doped TiO<sub>2</sub>, electron trapping by the metal centers, and the requirement of more expensive ion-implantation facilities (Yamashita *et al.* 1998; Wang *et al.* 1999). Since a breakthrough work by Asahi *et al.* (2001) in 2001 reported that doping TiO<sub>2</sub> with N can enhance its photocatalytic activity for the degradation of methylene blue under visible light irradiation, there has been a fruitful research strategy to narrow the band gap of TiO<sub>2</sub> and extend the light response range towards the visible region by doping with non-metal and transition metals (Inturi *et al.* 2014; Giannakasa *et al.* 2016). Among these non-metals and transition metals, N and V are the most promising dopants because the 2p orbital of N is the easiest to bind with the 2p orbital of O in the TiO<sub>2</sub> lattice to form the O-Ti-N structure (Schneider *et al.* 2014), while V ionic radii are almost the same as that of Ti<sup>4+</sup>; thus, V<sup>4+</sup> ions would probably be easier to substitute Ti<sup>4+</sup> ions in the crystal lattice of TiO<sub>2</sub> (Ren *et al.* 2015).

In this work, a V and N co-doping TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>) composite catalyst was prepared to enhance the removal of acid orange II (AO7) in a pulsed discharge plasma system. The aim of the work is to investigate the synergistic effects of pulsed discharge plasma and the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite photocatalyst. A series of characterization techniques, such as XRD, FTIR, SEM, XPS, etc., were carried out to determine the structure and surface chemical states of as-prepared composite catalyst. The enhancement effects of the doped amount of V and N, electrical factors and solution conditions on AO7 removal were investigated. The repetitive use of composite photocatalyst under pulsed discharge plasma was evaluated. The removal mechanism of AO7 from aqueous solution was also analyzed for the pulsed discharge plasma system with the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite.

## EXPERIMENTAL

### Materials

The MWCNTs (diameter > 50 nm, purity > 95%, tube length 10–20 nm) were purchased from Chengdu Organic

Chemistry Co., Ltd, China. Prior to use, the MWCNTs should be acidified with concentrated sulfuric acid and concentrated nitric acid, whose volume ratio was 3:1 as Liang *et al.* (2017) described. The temperature was maintained at 50 °C for 5 h and reflux condensation was conducted at the same time. The sphere  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> (diameter 1–3 mm) was supplied by Henan Sanyi Water Treatment Technology Co., Ltd, China. The AO7 (AR, C<sub>16</sub>H<sub>11</sub>N<sub>2</sub>NaO<sub>4</sub>S, molecular weight = 350.32 g·mol<sup>-1</sup>, purity 99.7%) was obtained from Shanghai Aladdin Bio-Chem Technology Co., Ltd, China. The silane coupling agent KH550 (C<sub>9</sub>H<sub>23</sub>NO<sub>3</sub>Si) was received from Jinan Xingfei Long Chemical Co., Ltd, China. The ammonium metavanadate (AR, NH<sub>4</sub>VO<sub>3</sub>, molecular weight = 116.98 g·mol<sup>-1</sup>) was purchased from Shanghai Shanpu Chemical Reagent Co., Ltd, China. The diethylamine (AR, (C<sub>2</sub>H<sub>5</sub>)<sub>2</sub>NH) was received from Tianjin Tianli Chemical Reagent Co., Ltd, China. All other reagents used in this study, including titanium butoxide, acetyl acetone, absolute alcohol, nitric acid, glacial acetic acid, etc., were all AR grade and were obtained from Tianjin Kermel Chemical Reagent Co., Ltd, China.

### Preparation and characterization of photocatalysts

The TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite was prepared according to our previous work (Li *et al.* 2016). The details of synthetic procedures of the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite catalyst were described in the Supplementary Material. A series of V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composites were prepared by changing the concentration of NH<sub>4</sub>VO<sub>3</sub> and (C<sub>2</sub>H<sub>5</sub>)<sub>2</sub>NH, and they are denoted as V<sub>x</sub>/N<sub>y</sub>-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, where x and y represented the molar amounts of V and N in the composite, respectively.

The prepared photocatalysts were characterized by a range of analytical techniques. The crystal structures of the prepared photocatalysts were measured by X-ray diffractometry (XRD, Bruker D8 Advance A25, Germany) in the range of 20–80° using Cu K $\alpha$  radiation. Fourier transform infrared spectroscopy (FTIR, Optics Tensor 27, USA) was used to analyze the composition information and chemical bonds of the samples. The surface morphologies of the photocatalysts were observed by a field emission scanning electron microscopy (FESEM, Hitachi S-4800, Japan). The surface chemical compositions of the photocatalysts were determined by X-ray photoelectron spectroscopy (XPS, EscaLab 250Xi, USA). UV-Vis diffuse reflectance spectroscopy of the samples was measured by a scanning UV-Vis spectrophotometer (UV-2600, Shimadzu, Japan) in the range of 300–800 nm. Photocurrent measurements were

carried out under visible light irradiation using a high-pressure xenon lamp.

## Experimental procedures

The experimental device diagram has been described in our previous paper (Li *et al.* 2016). In each batch experiment, 300 mL AO7 aqueous solution is treated, and the initial concentration of AO7 is 50 mg·L<sup>-1</sup>. The 5.0 g catalysts are filled between a high voltage multi-needle electrode and ground plate electrode. Prior to discharge treatment, air continuously bubbled into the reactor with a flow rate of 6.5 L·min<sup>-1</sup>. The flow rate of the wastewater was 100 L·min<sup>-1</sup>. The pulsed peak voltage and pulsed frequency used in the study is 22.8 kV and 75 Hz unchanged, respectively, unless special illustration.

A UV-Vis spectrophotometer was used as the analytical technique for monitoring the concentration reduction of the AO7 during the experiment because of its simplicity of use and ability to measure concentrations within a short time. A total organic carbon analyzer (TOC-L CPH, Shimadzu, Japan) was employed to determine the residual amounts of organic substances in the effluent to investigate the mineralization degree of the AO7 solution. The AO7 samples were drawn from the solution at 10 min intervals and analyzed using a UV-Vis spectrophotometer at 486 nm. A calibration curve is prepared from which the removal rate ( $\eta$ ) of AO7 is calculated using Equation (10):

$$\eta = \frac{C_0 - C_t}{C_0} \times 100\% \quad (10)$$

The energy density (ED, g·kW<sup>-1</sup>·h<sup>-1</sup>) of the reactor is defined as the quantity of removed AO7 (g) per discharge

power (kW·h) during treatment, as calculated by Equation (11):

$$ED = \frac{C_0 \times V \times \frac{C_0 - C_t}{C_0} \times \frac{1}{1000}}{\int_0^T U I dt} \quad (11)$$

where  $C_0$  is the initial concentration of AO7 (mg·L<sup>-1</sup>), and  $C_t$  is the concentration of AO7 after  $t$  min of treatment (mg·L<sup>-1</sup>);  $T$  (h) is the treatment time and  $U$  and  $I$  are discharge voltage (kV) and current (A), respectively;  $V$  (mL) is the solution volume.

## RESULTS AND DISCUSSION

### Characterization of the composite catalysts

The as-prepared samples were characterized by XRD and FTIR. As seen from Figure 1(a), all diffraction peaks from the TiO<sub>2</sub>-MWCNTs and V/N-TiO<sub>2</sub>-MWCNTs composites are attributable to anatase TiO<sub>2</sub>, which are consistent with the values in the standard card. No characteristic peaks attributed to V or N oxides are detected, indicating that the V and N ions were successfully incorporated into the crystal lattice of anatase TiO<sub>2</sub>. The (101) peak intensity of TiO<sub>2</sub>-MWCNTs decreases after V and N co-doping due to the formation of V-O-Ti or N-Ti-O linkages, which hinders the crystal growth as well as the agglomeration of TiO<sub>2</sub> particles (Chen *et al.* 2017a). It is also noticed that for the (101) plane peak, a small shift toward a lower diffraction angle occur in the peak position only for the V/N-TiO<sub>2</sub>-MWCNTs composite sample, suggesting that the majority

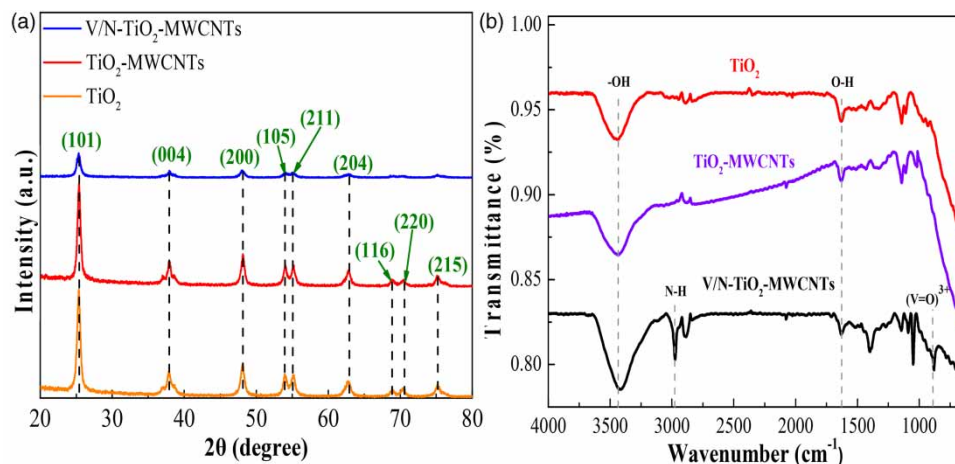


Figure 1 | XRD (a) and FTIR (b) spectra of prepared TiO<sub>2</sub>, TiO<sub>2</sub>-MWCNTs and V/N-TiO<sub>2</sub>-MWCNTs composites.

of V and N ions might be successfully incorporated into the crystal lattice of anatase  $\text{TiO}_2$  as  $\text{V}^{4+}$  or  $\text{N}^{4+}$  groups, and substituted for Ti and O in the crystal lattice of  $\text{TiO}_2$  (Zhong *et al.* 2014).

Figure 1(b) shows the compositional information and chemical bonds of  $\text{TiO}_2$ ,  $\text{TiO}_2$ -MWCNTs and V/N- $\text{TiO}_2$ -MWCNTs composites analyzed by FTIR spectroscopy. The band at approximately  $400\text{--}700\text{ cm}^{-1}$  represents a characteristic absorption peak of the Ti-O-Ti stretching vibration. The spectrum of the V/N- $\text{TiO}_2$ -MWCNTs composite shows that near  $860\text{ cm}^{-1}$  represents a characteristic stretching vibration peak of the  $(\text{V}=\text{O})^{3+}$  (Frederickson & Hausen 1963). The peak at  $1,180\text{ cm}^{-1}$  is related to the C-O stretching vibration band of MWCNTs, which may result from the strong interaction between  $\text{TiO}_2$ -MWCNTs nanoparticles (Sangari *et al.* 2015). The band at approximately  $3,000\text{ cm}^{-1}$  represents a characteristic absorption peak of

the N-H stretching vibration, which may improve the activity of the catalyst due to the formation of intermolecular hydrogen bonds between the amide bonds. The presence of -OH groups and water on the surface of the particles is confirmed by the appearance of a broad band near  $3,400\text{ cm}^{-1}$  for all samples. Another peak associated with O-H bending appeared at approximately  $1,640\text{ cm}^{-1}$  (Kuvarega *et al.* 2012). Given that most characteristic peaks of MWCNTs,  $\text{TiO}_2$ , V and N are observed, the existence of MWCNTs,  $\text{TiO}_2$ , V and N in V/N- $\text{TiO}_2$ -MWCNTs composite can be further confirmed.

Figure 2 shows the SEM images of the  $\text{TiO}_2$ ,  $\text{TiO}_2$ -MWCNTs and V/N- $\text{TiO}_2$ -MWCNTs composite. It can be seen from Figure 2(a) that the synthesized  $\text{TiO}_2$  nanoparticles possess a near spherical shape and some of them reunite. From Figure 2(b), the  $\text{TiO}_2$  nanoparticles appear to be homogeneously deposited on the MWCNTs, but show

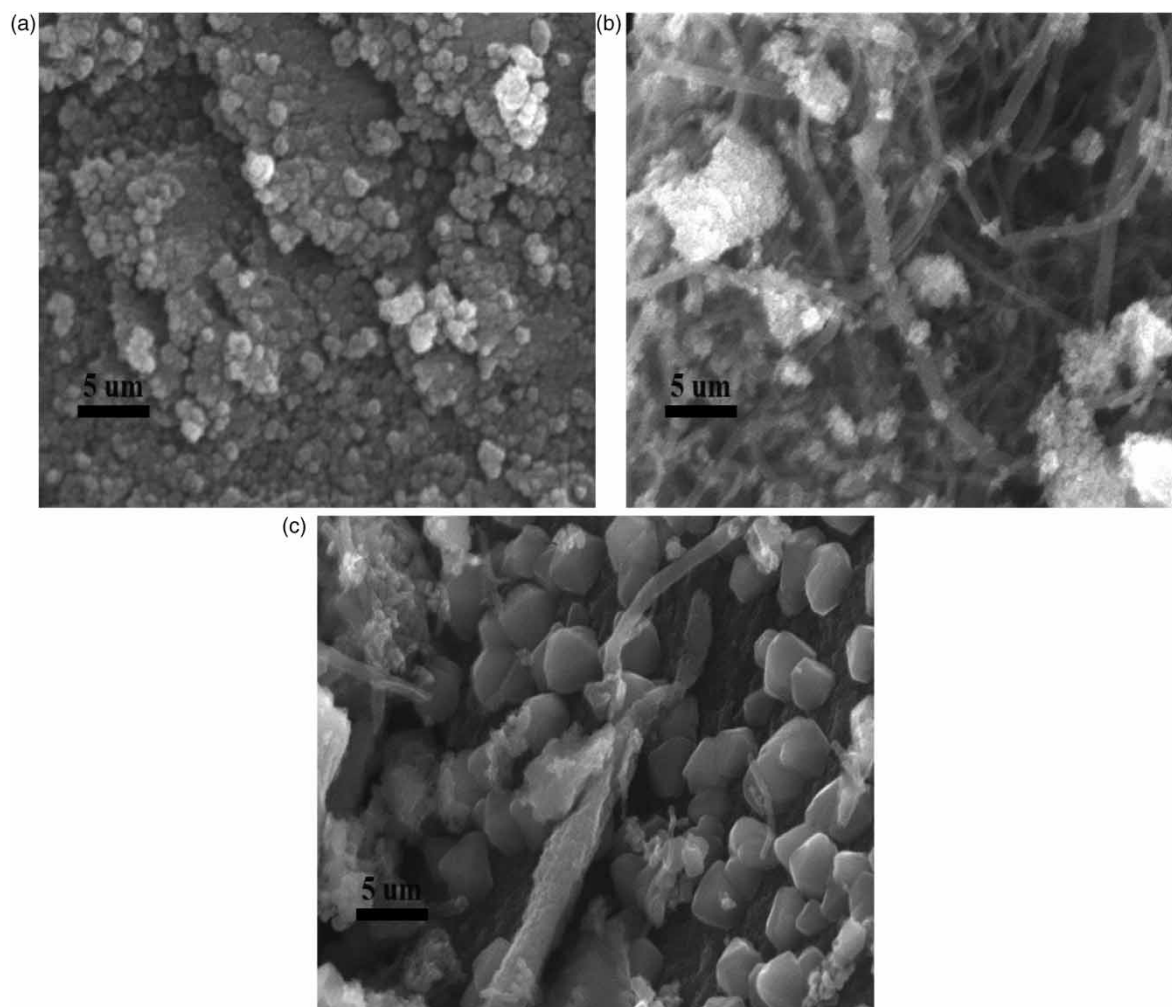


Figure 2 | SEM images of prepared catalysts:  $\text{TiO}_2$  (a),  $\text{TiO}_2$ -MWCNTs composite (b), V/N- $\text{TiO}_2$ -MWCNTs composite (c).

some agglomeration along the MWCNTs (Yan *et al.* 2006; Abd Hamid *et al.* 2014). The aggregation of TiO<sub>2</sub> over MWCNTs indicates the supporting role of MWCNTs as inhibiting the growth of TiO<sub>2</sub>. As shown in Figure 2(c), the V, N and TiO<sub>2</sub> nanoparticles are well attached to the MWCNTs. Compared with Figure 2(b), many small particles are observed, which represent that V and N elements are doped on the surface of TiO<sub>2</sub>. It is clear that V, N and TiO<sub>2</sub> nanoparticles are closely integrated and gathered on the MWCNTs, which is due to the high viscosity of the solid, thus reducing the dispersion of the particles. It is consistent with the XRD analysis that the structure of TiO<sub>2</sub> does not change after the loading of MWCNTs, V and N.

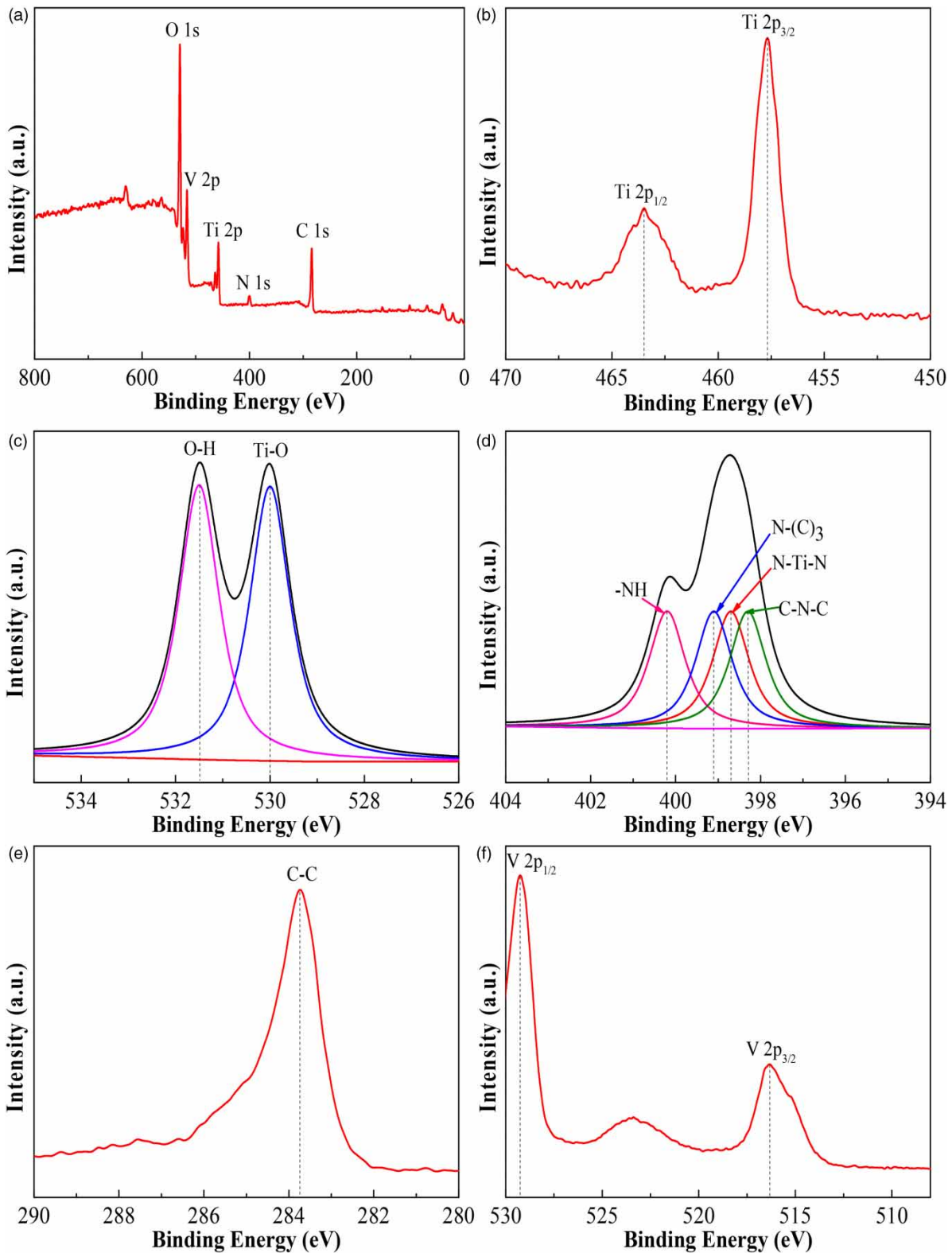
To further study the surface chemical composition and chemical state, the V/N-TiO<sub>2</sub>-MWCNTs composite was characterized by XPS. As shown in Figure 3(a), the signals of C, Ti, O, V and N are detected in the survey XPS spectrum of the V/N-TiO<sub>2</sub>-MWCNTs composite. No peaks of other elements are found, which means that the V/N-TiO<sub>2</sub>-MWCNTs composite heterojunction photocatalyst is mainly composed of C, Ti, O, V and N elements. The XPS signals of Ti 2p are observed at binding energies at approximately 457.6 eV (Ti 2p<sub>3/2</sub>) and 463.3 eV (Ti 2p<sub>1/2</sub>), as shown in Figure 3(b), which is the binding energy consistent with Ti<sup>4+</sup> oxidation state (Wang *et al.* 2015). The O 1s high resolution spectra of V/N-TiO<sub>2</sub>-MWCNTs composite are fitted to two peaks in Figure 3(c). The peak at approximately 530 eV corresponds to the Ti-O bond (Cong *et al.* 2011), which means that the chemical state of oxygen is the main lattice oxygen in TiO<sub>2</sub>. The peaks at 531.5 eV are assigned to the O-H bond. Figure 3(d) displays the high-resolution peak fitting spectra of N 1s. The four peaks at 398.3 eV, 398.7 eV, 399.1 eV and 400.2 eV correspond to sp<sup>2</sup> hybridized nitrogen (C-N-C), N-Ti-N, tertiary nitrogen (N-(C)<sub>3</sub>) and N-H, respectively (Li *et al.* 2005; Chen *et al.* 2014), which means that N elements are closely combined with MWCNTs and TiO<sub>2</sub> by forming new chemical bonds. Figure 3(e) shows the C 1s spectrum of V/N-TiO<sub>2</sub>-MWCNTs composite with one C 1s peak at 283.7 eV, which is attributed to a C-C bond from MWCNTs (Li *et al.* 2005). As shown in Figure 3(f), the V 2p spectra of the V/N-TiO<sub>2</sub>-MWCNTs composite have peaks at 516.9 eV (V 2p<sub>3/2</sub>) and 529.6 eV (V 2p<sub>1/2</sub>). The absorption peak at 516.9 eV is mainly due to V<sup>5+</sup> 2p<sub>3/2</sub> and V<sup>4+</sup> 2p<sub>3/2</sub>. Since the doped amount of V is very small, the peak shape is weak, and the 529.6 eV may be the corresponding absorption peak of V<sup>4+</sup> 2p<sub>3/2</sub>. The fitting data demonstrate that V<sup>4+</sup> is the dominant composition on the surface of doped V/N-TiO<sub>2</sub>-MWCNTs composite, which

suggests that the ionic radius of V<sup>4+</sup> is very close to that of Ti<sup>4+</sup>, and V<sup>4+</sup> can easily substituted for the Ti<sup>4+</sup> into the TiO<sub>2</sub> crystal lattice (Patel *et al.* 2014; Ren *et al.* 2015).

## Removal performance of AO7

### Comparison of the removal performance

The photocatalytic activity of the blank without catalyst (namely, plasma alone),  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composites in the removal of AO7 were compared in the pulsed discharge plasma system, respectively, and the results are shown in Figure 4. Figure 4(a) shows that plasma coupled with the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite shows better photocatalytic activity in the removal of AO7 compared to plasma coupled with TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite, TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> as well as plasma alone. Under the pulsed discharge plasma, 81.3% AO7 is removed by the TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite after 10 min. The removal rate of AO7 increases to 100% after 10 min by the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite. This may be due to the V and N co-doping causing TiO<sub>2</sub> lattice distortion and introducing a new impurity energy level in the band gap with V and N co-doping, which not only reduces the band gap of TiO<sub>2</sub> but also inhibits the recombination of the e<sup>-</sup>/h<sup>+</sup> pairs. Therefore, the synergistic effects of V and N enhance the photocatalytic activity of TiO<sub>2</sub> (Zhang *et al.* 2014). To gain an insight into the rate of different reaction systems, the kinetic model was also implemented to describe the removal rate. The reaction kinetics of AO7 for different treatment systems are shown in Figure 4(b) and the reaction rate constants are listed in Table 1. It is observed from Figure 4(b) that under pulsed discharge plasma, the removal rate of TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub>,  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and plasma alone to AO7 follow the pseudo first-order, as verified by  $\ln(C_t/C_0) = kt$ . The removal rate of plasma coupled with the TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composites to AO7 follow the pseudo second order kinetics model ( $t/q_t = 1/(kq_e^2) + t/q_e$ ). The V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite exhibits excellent photocatalytic activity, and the rate constant  $k$  ( $k = 1.0496 \text{ g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$ ) of the reaction is 5.99 and 72.39 times that of TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> ( $k = 0.1752 \text{ g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$ ) and TiO<sub>2</sub>/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> ( $k = 0.0145 \text{ g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$ ), respectively. It is further confirmed that MWCNTs and V/N-TiO<sub>2</sub> connected by a heterojunction can significantly improve the photocatalytic reaction rate.



**Figure 3** | XPS fully scanned spectra of V/N-TiO<sub>2</sub>-MWCNTs composite (a), XPS spectra of Ti 2p (b), XPS spectra of O 1s (c), XPS spectra of N 1s (d), XPS spectra of C 1s (e) and XPS spectra of V 2p (f).

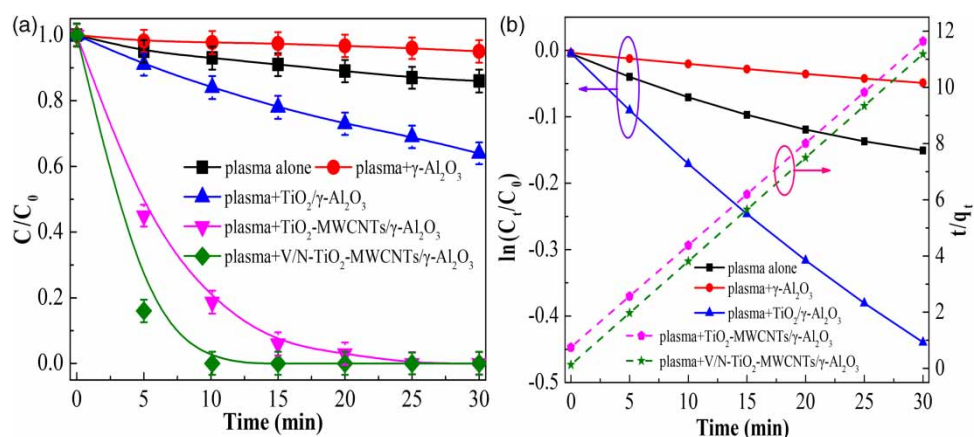


Figure 4 | Removal efficiencies and reaction kinetics of AO7 in different treatment systems.

Table 1 | Kinetic parameters of AO7 removal in different reaction systems

System	Response model	k	R <sup>2</sup>
Plasma alone	$\ln(C_t/C_0) = kt$	$k = 0.0049$	0.9830
Plasma + $\gamma\text{-Al}_2\text{O}_3$		$k = 0.0015$	0.9603
Plasma + $\text{TiO}_2/\gamma\text{-Al}_2\text{O}_3$		$k = 0.0145$	0.9946
Plasma + $\text{TiO}_2\text{-MWCNTs}/\gamma\text{-Al}_2\text{O}_3$	$t/q_t = 1/(kq_e^2) + t/q_e$	$k = 0.1752$	0.9844
Plasma + V/N-TiO <sub>2</sub> -MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$		$k = 1.0496$	0.9990

Note: k is reaction rate constant; R<sup>2</sup> is the rate equation fitting coefficient.

### The effects of the doped amount of V and N in composite on AO7 removal

The effects of the doped amount of V and N in the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite on AO7 removal in pulsed discharge plasma system are shown in Figure 5. As observed in Figure 5, the V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite exhibits the highest removal rate of 100% for AO7 under pulsed discharge plasma within 10 min. When n(V) = 0.1 mol, the removal rate of AO7 increases at first and then decreases with the increase of the amount of N. As the amount of V increases, the removal rate of AO7 increased initially and then decreased when n(N) = 0.05 mol. This may be due to overloaded co-doping of V and N in the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite that may result in channel plugging, and thus reduced photocatalytic activity of TiO<sub>2</sub>. With the decrease of V and N co-doping, the recombination opportunity of e<sub>cb</sub><sup>-</sup>/h<sub>vb</sub><sup>+</sup> pairs is reduced, which improves the photocatalytic activity of the catalyst. With the further reduction of V and N content in the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite, the photocatalytic activity of

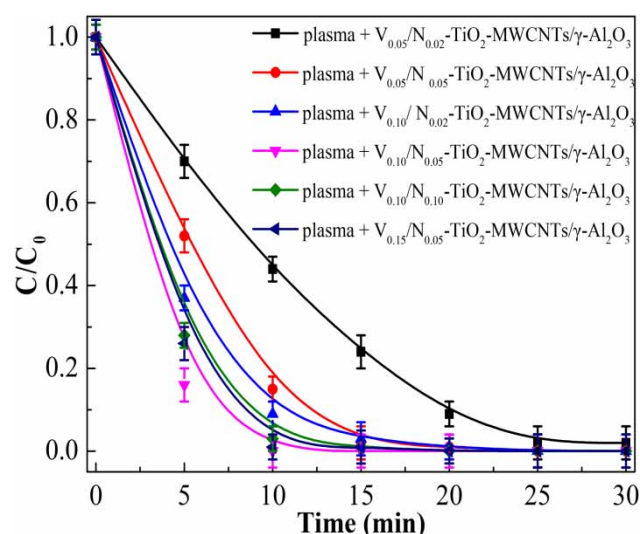


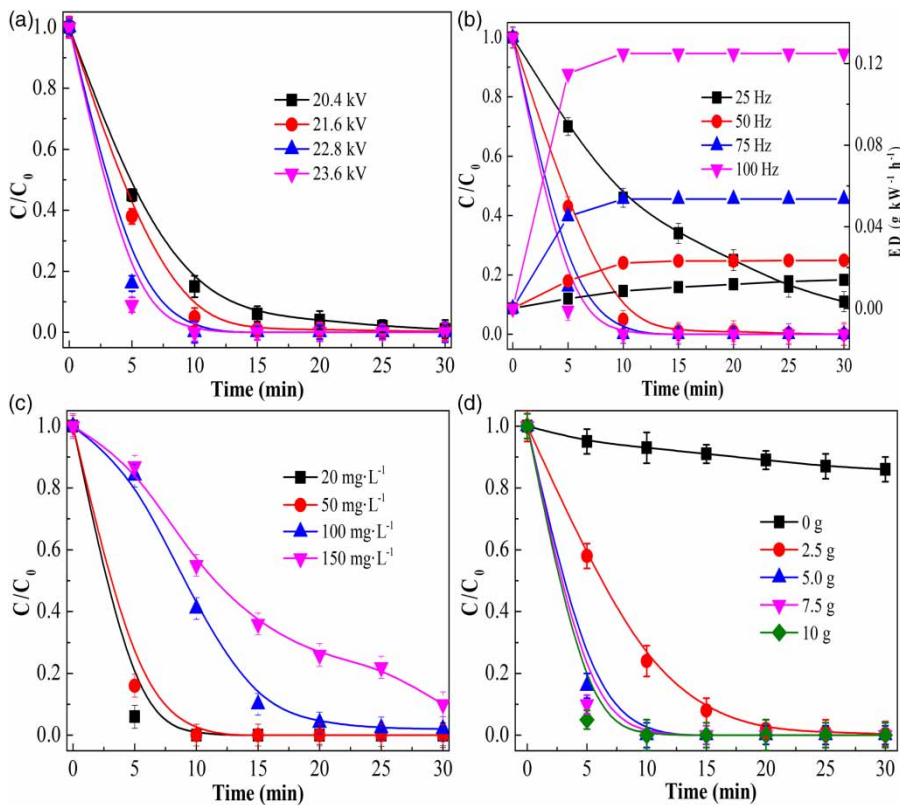
Figure 5 | Effects of doped ratio of V and N in the composite on AO7 removal for pulsed discharge plasma system.

TiO<sub>2</sub> decreases because it does not cause TiO<sub>2</sub> lattice distortion. It is an indication that the introduction of appropriate amounts of V and N ions into the TiO<sub>2</sub> lattice might effectively restrain the recombination rate of photogenerated e<sub>cb</sub><sup>-</sup>/h<sub>vb</sub><sup>+</sup> pairs, resulting in enhancing the photocatalytic activity of TiO<sub>2</sub>. Thus, V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite was used in this study.

### Effects of different electrical factors and solution conditions on AO7 removal

Figure 6(a) illustrates the effects of pulsed peak voltage on AO7 removal in a pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma\text{-Al}_2\text{O}_3$  composite system. As shown in Figure 6(a), the removal rate of AO7 is enhanced with





**Figure 6** | Effects of pulsed peak voltage (a), pulsed frequency (b), initial concentration (c) and quantity of catalyst (d) on AO7 removal.

increasing pulsed peak voltage. At 20.4 kV, 85.0% of AO7 is removed after 10 min. The removal rate of AO7 increases to 100.0% after 10 min at 23.6 kV. With pulsed peak voltage increases, the electric field intensity is enhanced, and more active species are produced, such as  $O_3$ ,  $\cdot O$ , and  $\cdot OH$ . In addition, with the voltage raised, the intensity of UV light and shockwave are also enhanced (Zhang *et al.* 2010; Chen *et al.* 2017b). This stronger irradiation can promote the formation of photogenerated  $e_{cb}^-$  and  $h_{vb}^+$  in the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite. The photogenerated  $e_{cb}^-$  and  $h_{vb}^+$  effectively promote the removal of AO7. Furthermore, the  $e_{cb}^-$  and  $h_{vb}^+$  facilitate the generation of reactive species, such as  $\cdot OH$  and  $\cdot O_2^-$ , on the catalyst when the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite' surface is irradiated (Tang *et al.* 2013). Figure 6(b) presents the effects of pulsed frequency on AO7 removal in the pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite system. After 10 min of discharge treatment, the removal rate of AO7 is 54.0%, 95.0%, 100.0% and 100.0% with pulsed frequencies of 25 Hz, 50, 75 and 100 Hz under a pulsed peak voltage of 22.8 kV, respectively. It is obvious that the removal rate of AO7 is promoted with pulsed frequency increases. This can be explained by more energy

being injected into the reactor per unit time at higher pulse repetitive frequency, resulting in a higher energy density per unit volume of the reactor (see Figure 6(b)). More micro-discharges are produced during each unit of time and the amount of high energetic electrons increases. These high energy electrons and generated species not only lead to more collision probabilities with AO7 in solution but also induce the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite to remove AO7 in solution (Snyder & Anderson 2001). Thus, the removal rate of AO7 is improved. Figure 6(c) displays the effects of the initial concentration on AO7 removal in the pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite system. It can be seen from Figure 6(c) that the removal rate of AO7 decreases as the initial concentration of AO7 increases. At the initial concentration of 50.0 mg·L<sup>-1</sup>, 100.0% of AO7 is removed within 10 min. When the initial concentration of AO7 reaches 150.0 mg·L<sup>-1</sup>, the removal rate decreases to 45.0%. With the increasing AO7 concentration, more organic substances (AO7 and intermediates) are adsorbed on the surface of the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalysts, and the generation of active species, such as  $\cdot OH$ ,  $\cdot O$ , H<sub>2</sub>O<sub>2</sub> and O<sub>3</sub> is restrained. Additionally, adsorbed AO7 dye molecules at

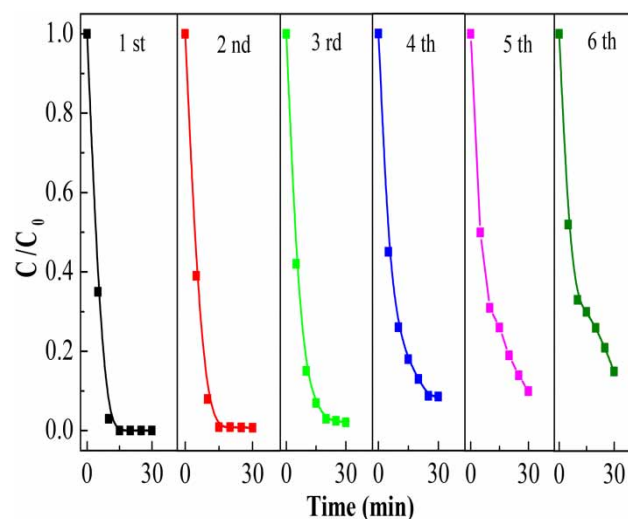
high dye concentrations might block the active areas on the surface of the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite, causing minimal development of •OH radicals, which in turn results in the lower removal rate of AO7. Figure 6(d) depicts the effects of the quality of V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite on the removal rate of AO7 in the pulsed discharge plasma system. The removal rate of AO7 distinctly increases when the amount of V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite increases from 0 to 5.0 g. When the catalyst amount is 5.0 g, the removal rate of AO7 can reach 100.0% after 10 min of treatment in a pulsed discharge plasma system. A catalyst increase from 5.0 to 10.0 g in the amount exhibits a slow increase. These suggest that at lower levels of catalyst content, increasing the amount of catalyst provides more total surface area and active sites for both adsorption and photocatalysis, resulting in the enhancement of the removal rate. However, a further increase in the catalyst amount may cause light scattering and a screening effect affecting the specific activity of the catalyst (An *et al.* 2014). Additionally, it is important to keep the cost of the treatment low if it is to be industrially utilized; therefore, the optimum catalyst amount appears to be 5.0 g in this study.

### Recycling experiments

The repetitive use of the composite is very important for its practical application. Hence, the stability of the V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite was evaluated by reusing the catalyst 6 times for the removal of AO7. After each use, the catalyst was washed with ethanol, then acetone, and then dried in an oven at 60 °C for 1 h. As shown in Figure 7, the catalyst displays sufficient stability and reaches a maximum removal rate of 85.0% after 6 cycles under pulsed discharge plasma. We must admit that the catalyst had a loss after six experiments but the remaining 85% proved its potential catalytic performance and its value for practical application.

### Mechanism of enhanced composite photocatalysis induced by pulsed discharge plasma

Figure 8 shows the UV-Vis DRS spectroscopy of TiO<sub>2</sub>, TiO<sub>2</sub>-MWCNTs and V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composites. As shown in Figure 8(a), the spectra are characterized by an intense fundamental absorption due to anatase TiO<sub>2</sub> in the region of between 350 and 400 nm. Meanwhile, the absorption edge of the TiO<sub>2</sub>-MWCNTs and V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composites exhibits a dramatic red shift when



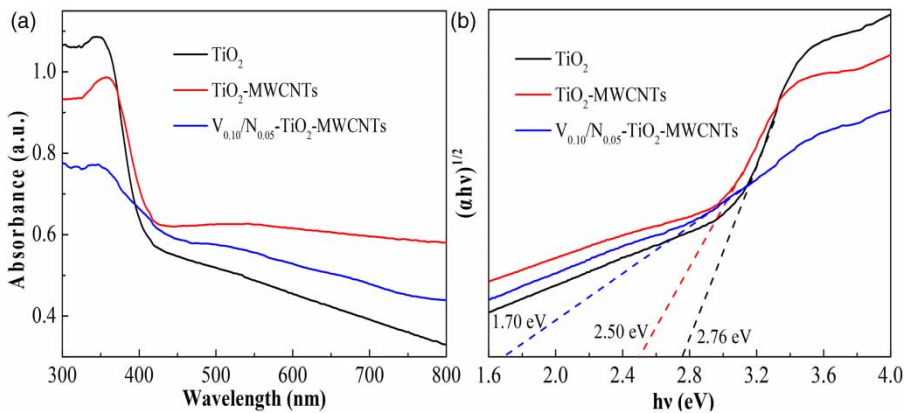
**Figure 7** | Recyclability studies of the V/N-TiO<sub>2</sub>-MWCNTs composite for AO7 removal in pulsed discharge plasma system.

compared with that of the pure TiO<sub>2</sub>, which, due to the presence of MWCNTs, V and N doping, results in decreasing the energy gap for electron transition. Although TiO<sub>2</sub>-MWCNTs composite has better absorbency and absorption edge range than V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composite, there are many factors that affect the photocatalytic activity of the catalyst. Therefore, it is not correct to think that the better the visible light absorption, the higher the catalytic activity. The doping of V and N can produce an effective interfacial electron transfer, which is helpful to the separation of e<sup>-</sup><sub>cb</sub>/h<sup>+</sup><sub>vb</sub> pairs on V/N-TiO<sub>2</sub>-MWCNTs and the catalytic active point of the composite.

As shown in Figure 8(b), the band gap energies of the direct transition semiconductors were estimated by plots of  $(\alpha h\nu)^{1/2}$  vs photon energy on the basis of the following formula (Ilkhechi *et al.* 2016):

$$(\alpha h\nu)^{1/2} = A (h\nu - E_g) \quad (12)$$

where  $\alpha$ ,  $h$ ,  $\nu$ ,  $A$  and  $E_g$  represent the absorption coefficient, Planck's constant, optical frequency, constant and band gap, respectively. It can be estimated from Figure 8(b) that the band gap energies of TiO<sub>2</sub> and TiO<sub>2</sub>-MWCNTs are 2.76 eV and 2.50 eV, respectively. The band gap of V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composite is significantly reduced to approximately 1.70 eV. This is because V and N introduce impurity energy levels at the conduction band (CB) bottom and the valence band (VB) edge, and the increase of impurity energy series leads to a further decrease of the band gap. In addition, the increase of impurity energy level also greatly



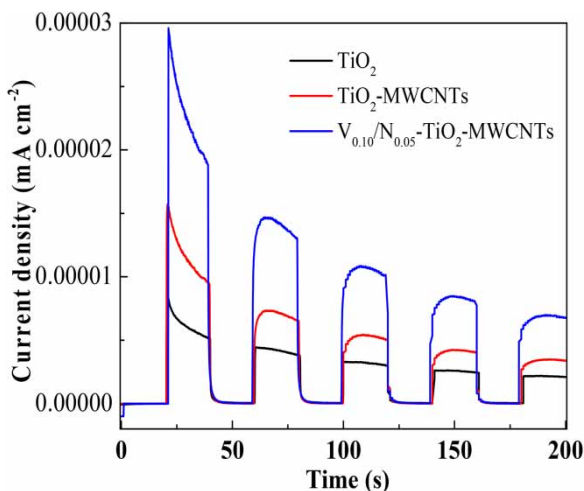
**Figure 8** | UV-Vis spectra (a) and plots of  $(\alpha hv)^{1/2}$  vs photon energy (b) of the prepared  $\text{TiO}_2$ ,  $\text{TiO}_2$ -MWCNTs and  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composites.

reduces the VB electron's transition energy; that is, the VB electron can transfer to the CB with less energy absorption, and also promote the effective separation of photogenerated  $e^-$  and  $h^+$ , thereby enhancing the photocatalytic properties of  $\text{TiO}_2$ . This confirms that adding a small amount of N and V ion dopants could alter the absorption feature significantly.

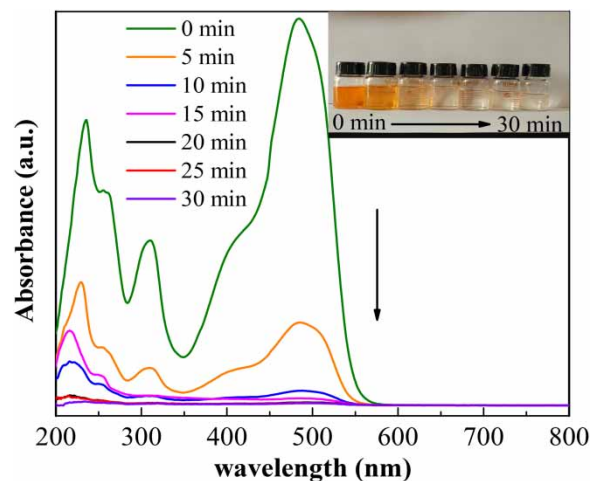
Figure 9 shows the photocurrent response curves of the photoelectrodes consisting of  $\text{TiO}_2$ ,  $\text{TiO}_2$ -MWCNTs and  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composites. It is found that the stable photocurrent values of  $\text{TiO}_2$ -MWCNTs and  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composites are nearly 2 and 4 times higher than that of pure  $\text{TiO}_2$ . It can be ascribed to V and N co-doping improving the separation rate of photogenerated  $e^-$  and  $h^+$ , and results in the enhancement of the photocurrent. The N anion and V cation co-doping  $\text{TiO}_2$ -

MWCNTs can effectively reduce the complex center because co-doping avoids the defect band caused by single doping. The V and N co-doping catalyst has a better optical response capability, which is more advantageous to the generation and separation of photonic  $e^-$  and  $h^+$ .

Figure 10 displays the UV-Vis absorption spectra changes of AO7 solution degraded by  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composite induced by pulsed discharge plasma at different treatment times. It is found that AO7 has four absorption peaks at 235, 256, 310, and 486 nm and a shoulder peak at 425 nm. The peak at 486 nm suggests the presence of the hydrazone form (main adsorption peak), whereas the shoulder peak at 425 nm indicates the presence of the azo form. Under the given conditions, a rapid decoloration of the AO7 solution is fulfilled within 10 min. Moreover, with the disappearance of the characteristic peak at 486 nm, the intensities of the peaks at 235, 256



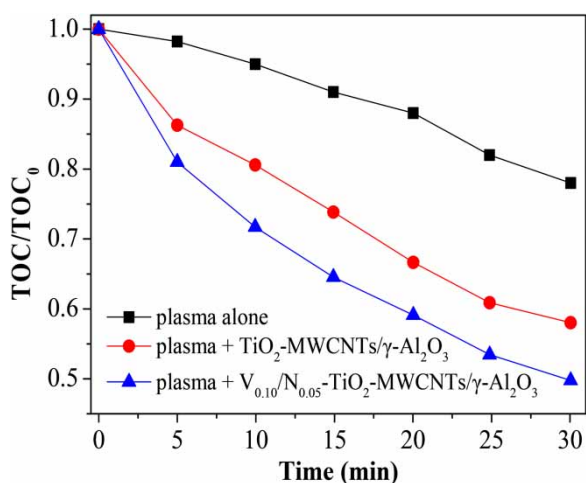
**Figure 9** | The photocurrent response curves of the photoelectrodes consisting of  $\text{TiO}_2$ ,  $\text{TiO}_2$ -MWCNTs and  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composites.



**Figure 10** | The UV-Vis absorption spectra changes of AO7 solution at discharge plasma treatment times with  $\text{V}_{0.10}/\text{N}_{0.05}$ - $\text{TiO}_2$ -MWCNTs composites.

and 310 nm are also decreased without the formation of new absorption peaks, which indicates that some structures are broken by the action of pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs composite. In addition, it can also be inferred from Figure 10 that radicals generated during the reaction process reacted with the azo group (-N=N-) responsible for the characteristic color of the dye, whereas the radical reaction with the other four groups is weak. It may be due to the -N=N- in the AO7 molecule being unstable and prone to be attacked by the activated species. Thus, the generated radicals easily react with the -N=N- and make the group rupture during the oxidation reaction. Furthermore, no new peaks came into being both in the

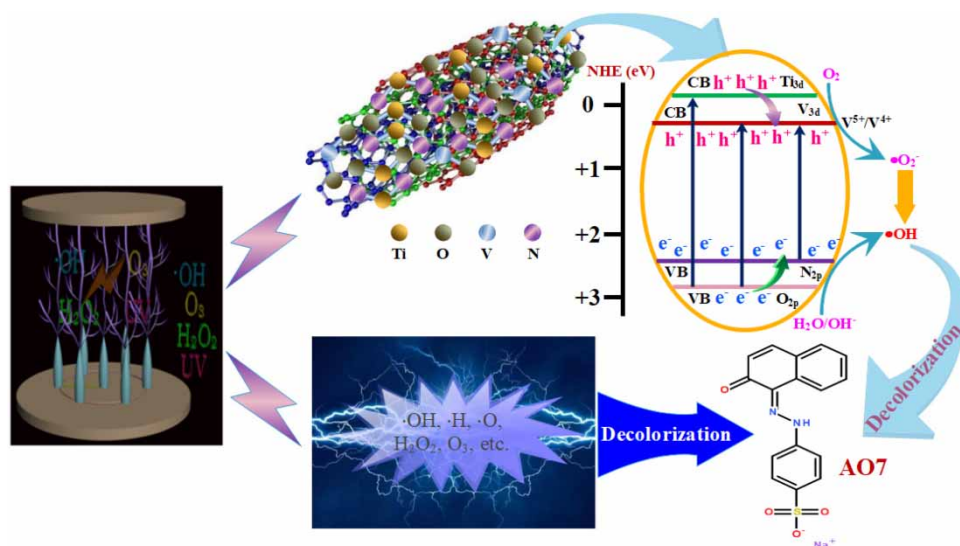
ultraviolet area and in the visible light area, which indicate the naphthyl and benzene ring, containing fragments generated during the decoloration process, were further degraded (Guo et al. 2016). As a good indicator of the mineralization of organic pollutants, the variation of TOC was monitored. As shown in Figure 11, the TOC removal is 50.2% for the pulsed discharge plasma induced V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composite system, which is 2.3 and 1.2 times higher than that in the pulsed discharge plasma system alone and pulsed discharge plasma induced TiO<sub>2</sub>-MWCNTs composite system, respectively. The results confirm that the synergistic effects of pulsed discharge plasma and V/N-TiO<sub>2</sub>-MWCNTs composite have good removal rates and certain mineralization of AO7 (Figure 12). The relatively low removal of TOC indicates that there is still a portion of the intermediate organics in the solution. The reason may be that AO7 molecules in solution are not directly mineralized into CO<sub>2</sub> and H<sub>2</sub>O during the removal process. It is degraded into some intermediate products through degradation of chromophoric groups and benzene-like ring structure, and then degraded into CO<sub>2</sub> and H<sub>2</sub>O.



**Figure 11** | The changes of TOC after different discharge plasma treatment times with V<sub>0.10</sub>/N<sub>0.05</sub>-TiO<sub>2</sub>-MWCNTs composite.

## CONCLUSIONS

The synergistic effects of the pulsed discharge plasma and V/N-TiO<sub>2</sub>-MWCNTs/γ-Al<sub>2</sub>O<sub>3</sub> composite photocatalyst significantly enhance the removal rate of the azo dye AO7 from aqueous solution. Under pulsed discharge plasma, almost 100% of AO7 is removed by the V/N-TiO<sub>2</sub>-



**Figure 12** | The proposed mechanism of synergistic effect of pulsed discharge plasma and V/N-TiO<sub>2</sub>-MWCNTs composite for AO7 removal from aqueous solution.

MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite after 10 min under optimal conditions. Removal of AO7 can be significantly enhanced by the pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite because V and N co-doping causes TiO<sub>2</sub> lattice distortion and introduces a new impurity energy level, which not only reduces the band gap of TiO<sub>2</sub> but also inhibits the recombination of the e<sub>cb</sub><sup>-</sup>/h<sub>vb</sub><sup>+</sup> pairs. The doping ratio V and N is important to enhance the activity of TiO<sub>2</sub> because overloaded doping of V and N may result in channel plugging. The removal rate of AO7 is also affected by the pulsed discharge peak voltage, pulsed discharge frequency, initial concentration of the solution and dosage of the composite catalyst. For application purposes, V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite catalysts demonstrate an adequate recycling performance, proving it to be a viable option for degrading organic pollutants from aqueous solution in a pulsed discharge plasma system. Pulsed discharge plasma induced V/N-TiO<sub>2</sub>-MWCNTs/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> composite photocatalyst can effectively break down AO7, but cannot completely break AO7 down into CO<sub>2</sub> and H<sub>2</sub>O.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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