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EFFECT OF WO₃ ON THE MORPHOLOGY AND PHOTODEGRADATION OF DIMETHYL PHTHALATE OF TiO₂ NANOTUBE ARRAY PHOTOELECTRODE

WO₃ modified TiO₂ nanotube array (WO₃/TNAs) photoelectrodes were fabricated via electrochemical deposition on TNAs/Ti photoelectrodes. The morphology and structure of WO₃/TNAs photoelectrodes were investigated by scanning electron microscopy (SEM) and X-ray diffractometer (XRD). The effects of deposition potential, deposition duration, Na₂WO₄ concentration, and calcination temperature on the morphology and the photocatalytic activity were investigated. The results showed that suitable amounts of WO₃ promoted the photocatalytic activity of TNAs photoelectrodes for the degradation of dimethyl phthalate (DMP). The optimal conditions for the fabrication of WO₃/TNAs photoelectrodes were as follows: deposition voltage 3.0 V, 10 min deposition duration, 0.01 mol/dm³ Na₂WO₄ concentration, 1.5 cm electrode gap, and 550 °C annealing temperature. The degradation rate of DMP reached 77% after 60 min of illumination by WO₃/TNAs photoelectrode. Additionally, WO₃/TNA photoelectrodes possessed superb stability for maintaining a high DMP degradation efficiency at more than 75% after 10 times of successive use with 60 min irradiation for each cycle. The enhancement of photocatalytic performance by the efficient combination of WO₃ with TNAs would provide a theoretical basis for the practical application of WO₃/TNA photoelectrodes in water treatment.

1. INTRODUCTION

Phthalates (PAEs) are widely used as a plasticizers in industry. As one kind of PAEs, dimethyl phthalate (DMP) could accumulate in biological organisms and disturb the endocrine system even at a low concentration. DMP is a ubiquitous environmental pollutant and is listed as one of the priority pollutants by American EPA as well as by

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China's Ministry of Environmental Protection. Therefore, investigating methods for DMP degradation is critically important. Several such methods including photocatalytic oxidation [1–3], electrochemical degradation [4, 5], adsorption [6, 7] and sonoelectrolysis [8, 9] have been investigated.

In the last decade, TiO₂ nanotube arrays (TNAs) have received intense attention. They are considered one of the most promising photocatalysts for their remarkable ability of charge transport and superior oxidation [10–12]. However, TNAs photocatalysts, with band gap of 3.0–3.2 eV, could be activated only by UV radiation ($\lambda < 380$ nm) which accounts to less than 5% of solar energy on the Earth's surface [13].

To use the sunlight in an efficient way for TNAs photocatalyst, various doping materials have been used, such as C [14, 15], Pd [16], In [17], Bi [18], CdTe [19], CdS [20, 21], WO₃ [22] and Sb₂S₃ [23]. It is well known that WO₃ has a slightly lower conduction band (CB) than that of TiO₂, thus the photoelectrons could transfer from the CB of TiO₂ to the CB of WO₃ and the recombination of charge carriers is reduced [22].

In our previous study [24, 25], WO₃ was successfully incorporated onto TNAs surface by a convenient cycle pulse electrodeposition method in tungstate solution. In this research, the effects of deposition potential, the Na₂WO₄ concentration and the annealed temperature on the photodegradation of DMP were investigated.

2. EXPERIMENTAL

Chemicals and materials. Titanium foils (purity > 99.9%, 0.2 mm thick) were obtained from Baoji Titanium and Nickel Manufacture Limited Company, China. All chemicals were obtained as analytical reagent grade and used without further purification. The experimental solutions were prepared with doubly distilled water.

Sample preparation and characterization. The TNAs photoelectrode (20×10 mm) fabricated by our group [12] and platinum (Pt) sheet were separately used as a cathode and anode in 0.1 mol/dm³ Na₂SO₄ solution with various amounts of Na₂WO₄ (0.002, 0.005, 0.01, 0.03, 0.05 mol/dm³). The deposition process was conducted at various potentials (1, 3 and 5 V) and times (2–60 min). Then the samples were immediately rinsed with deionized water and dried at 378 K for 60 min. Finally the photoelectrodes were annealed at 400 °C, 550 °C, 600 °C and 700 °C each for 120 min. The surface morphology of fabricated photoelectrodes was studied by SEM (America QUANTA200F). The crystal structure was examined using X-ray diffractometer (XRD, Rigaku D/max-rb) with CuK_α radiation ($\lambda = 1.5418$) at 0.02° intervals of 2θ over the range of 10–90°.

Photocatalytic activity. The photocatalytic performance of WO₃/TNAs photoelectrode was investigated using DMP aqueous solution (40 cm³) in a single-compartment cylindrical quartz reactor. The concentration of DMP was 20 mg/dm³. Before photoreaction,

the sample solution was stirred in the dark for 30 min to reach adsorption/desorption equilibrium, then the sample solution, under magnetic stirring, was illuminated. A 75 W xenon lamp of was used as an external light source with the light intensity of 30.5 mW/cm² which would last 60 min. The DMP solution was collected at specific time intervals and analyzed immediately. The concentration of DMP was determined by the high performance liquid chromatography (HPLC, LC-20A, Shimadzu, Japan) with Inertsil ODS-SP column (150×4.6 mm, 5 μm). The detection optical wavelength was 228 nm. The mobile phase was mixture of methanol with water (9:1) with the flow rate of 1.0 cm³/min. The column temperature was 30 °C.

The degradation rate of DMP was calculated using the following formula:

$$D = \frac{C_0 - C}{C_0} \times 100\% \quad (1)$$

where C_0 is the initial concentration, C is the concentration after a certain period of illumination.

3. RESULTS AND DISCUSSIONS

3.1. MORPHOLOGY AND CRYSTAL STRUCTURE

Figure 1 shows the morphology of WO₃/TNAs photoelectrodes fabricated at various deposition potentials in 0.01 mol/dm³ Na₂WO₄ and 0.1 mol/dm³ Na₂SO₄.

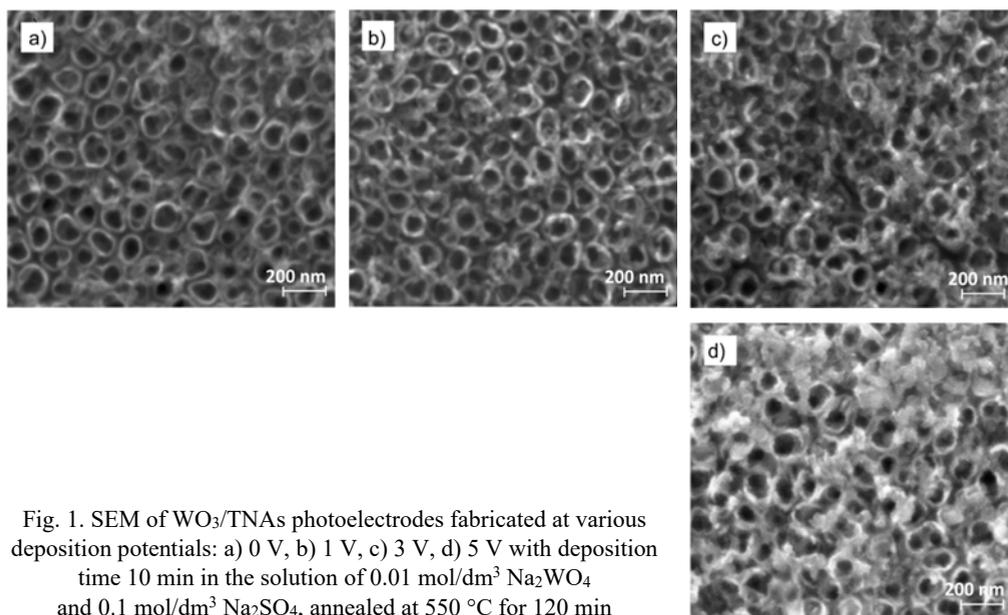


Fig. 1. SEM of WO₃/TNAs photoelectrodes fabricated at various deposition potentials: a) 0 V, b) 1 V, c) 3 V, d) 5 V with deposition time 10 min in the solution of 0.01 mol/dm³ Na₂WO₄ and 0.1 mol/dm³ Na₂SO₄, annealed at 550 °C for 120 min

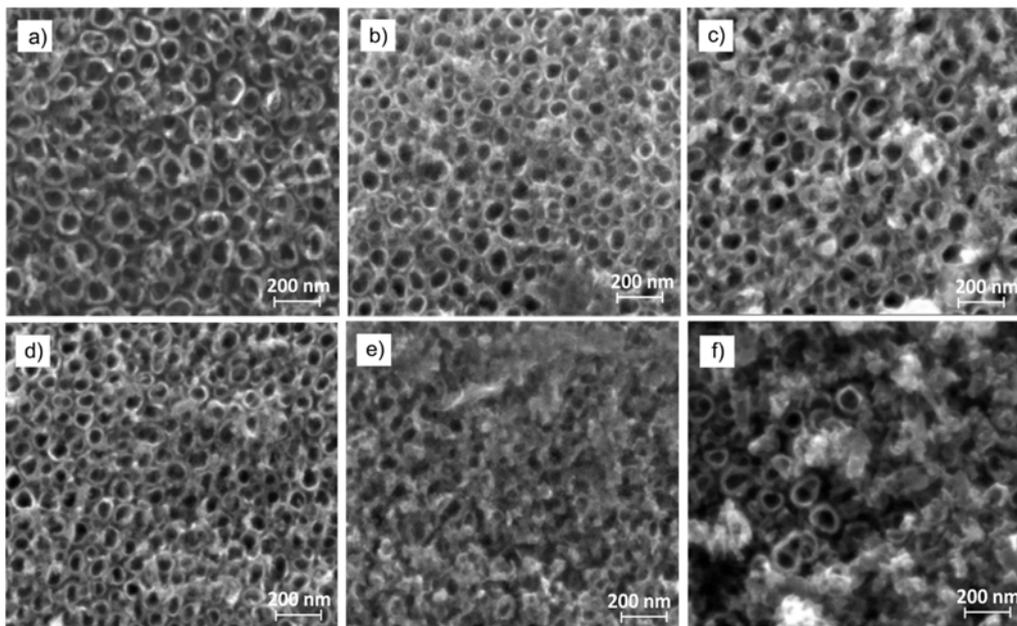


Fig. 2. SEM of WO_3/TNAs photoelectrodes fabricated at various Na_2WO_4 concentrations: a) 0, b) 0.002 mol/dm³, c) 0.005 mol/dm³, d) 0.01 mol/dm³, e) 0.03 mol/dm³, f) 0.05 mol/dm³ with the deposition time 10 min, deposition potential 3 V, annealed at 550 °C for 120 min

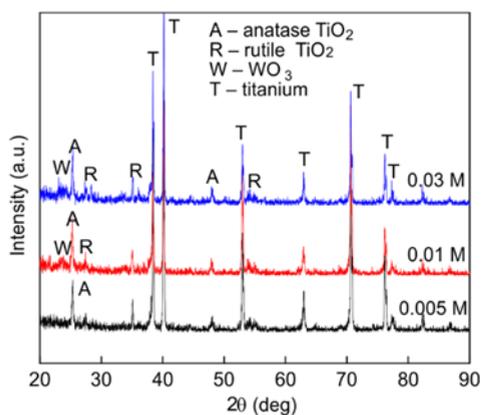


Fig. 3. XRD of WO_3/TNAs photoelectrodes fabricated at various Na_2WO_4 concentrations with the deposition time 10 min, deposition potential 3 V, annealed at 550 °C for 120 min

The results showed that all WO_3/TNAs photoelectrodes have ordered nanotube arrays with the tube diameter of 90–100 nm and the wall thickness of 13–15 nm. There was no obvious difference between the photoelectrodes fabricated at 0 V and 1 V (Figs. 1a and 1b). However, the sediment was clearly present on the top of nanotube arrays when the deposition potential was 3 V (Fig. 1c). When the deposition potential was 5 V (Fig. 1d), some tubes were blocked. The results in Fig. 1 indicate that as the

deposition potentials increased, the sediment gradually increased as well. The morphology of WO₃/TNAs photoelectrode fabricated at various Na₂WO₄ concentrations is shown in Fig. 2. The crystal structure of WO₃/TNAs photoelectrode annealed at 550 °C for 120 min is shown in Fig. 3.

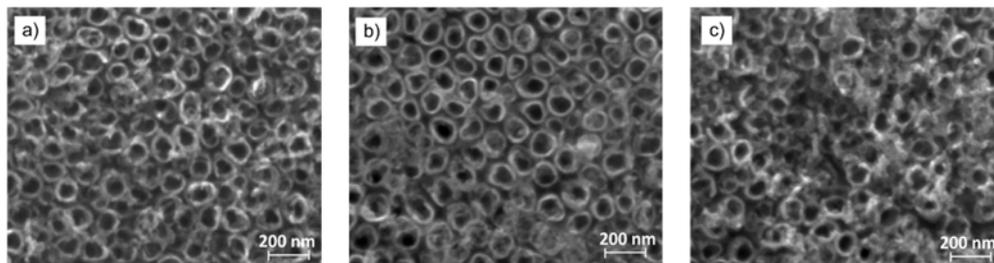


Fig. 4. SEM of WO₃/TNAs photoelectrodes fabricated at various deposition times: a) 0 min, b) 5 min, c) 10 min, d) 20 min, e) 60 min with the deposition potential 3 V, Na₂WO₄ concentration of 0.01 mol/dm³, annealed at 550 °C for 120 min

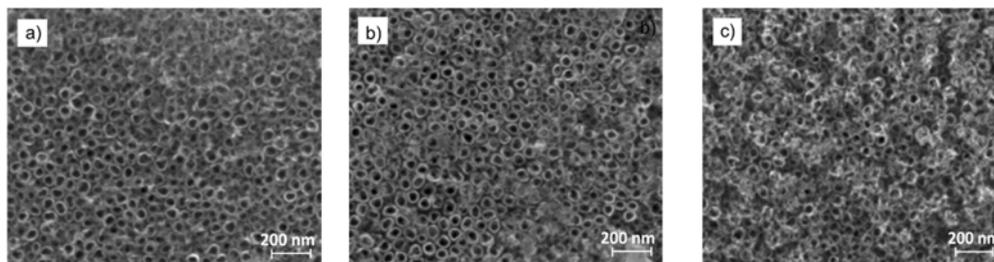


Fig. 5. SEM of WO₃/TNAs photoelectrodes fabricated at various annealing temperatures: a) unannealed, b) 400 °C, c) 550 °C, d) 600 °C, e) 700 °C with the deposition potential 3 V, deposition time 10 min, and Na₂WO₄ concentration 0.01 mol/dm³

The results show that with an increasing concentration of Na₂WO₄, the sediment on the top of nanotube array gradually increased (Figs. 2a–d). When the concentration

of Na_2WO_4 was 0.03 mol/dm^3 , some nanotubes were blocked (Fig. 2e). A thick sediment covered the surface of nanotube array when the concentration of Na_2WO_4 increased to 0.05 mol/dm^3 (Fig. 2f). In Figure 3, a characteristic peak of WO_3 was found at 23.5° when the concentration of Na_2WO_4 increased from 0.01 to 0.03 mol/dm^3 which indicated that WO_3 was incorporated successfully onto TNAs. When the concentration of Na_2WO_4 was low at 0.002 mol/dm^3 , WO_3 was not detected. As the Na_2WO_4 concentration increased, the amounts of WO_3 incorporated onto TNAs increased as well.

The morphology of WO_3/TNAs photoelectrodes annealed at various temperatures is shown in Fig. 5. The morphology of WO_3/TNAs photoelectrode annealed at 400°C showed no difference with that of unannealed photoelectrodes (Figs. 5a–b, respectively). When the photoelectrode was annealed at 550°C or 600°C , some fine particles emerged on the surface (Figs. 5c–d) for the aggregation of WO_3 . When the annealed temperature was 700°C , the nanotube collapsed and turned to worm state (Fig. 5e).

3.2. PHOTOCATALYTIC PERFORMANCE

The photodegradation rates of WO_3/TNAs photoelectrodes fabricated at various deposition potentials are shown in Fig. 6. When the deposition potential was lower than 3.0 V , upon its increase the photodegradation rate of DMP increased too and reached the peak of 82.6% . The degradation rate of DMP decreased when the potential exceeded 3.0 V .

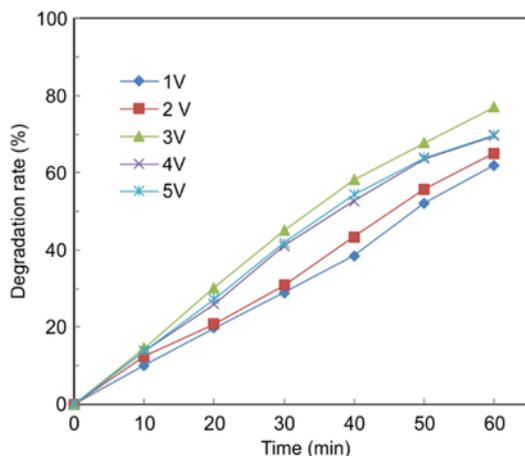


Fig. 6. Time dependences of the evolution of DMP photodegradation rate for WO_3/TNAs photoelectrodes fabricated at various deposition potentials; deposition time 10 min , Na_2WO_4 concentration 0.01 mol/dm^3 , initial DMP concentration 20 mg/dm^3 , and annealing temperature 550°C

The amount of WO_3 sediment on the surface of TNAs increased gradually with the increase of the deposition potential (Fig. 1). Compared with TNAs, WO_3 could absorb much more light and would trap the photogenerated electrons. Thus, the light quantum

efficiency was enhanced. However, too much WO₃ would block the mouth of nanotubes (Fig. 1) and therefore inhibited the light adsorption and the transfer of photogenerated electrons of TNAs, leading to a decreased rate of DMP photodegradation. The results verified that suitable amounts of WO₃ were beneficial to the photocatalytic activity of TNAs photoelectrode.

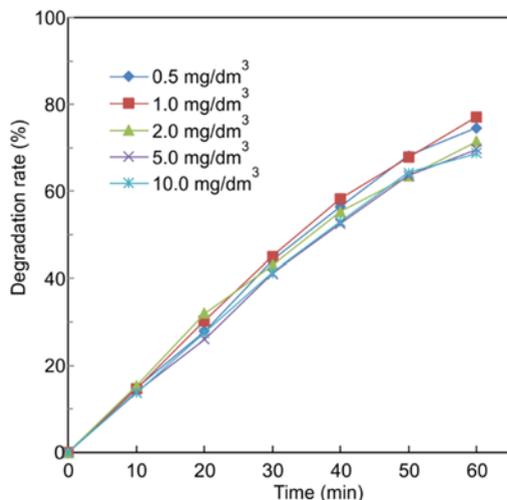


Fig. 7. Time dependences of the DMP photodegradation rate for WO₃/TNAs photoelectrodes fabricated at various concentrations of Na₂WO₄, deposition time 10 min, deposition potential 3 V, annealing temperature of 550 °C, initial DMP concentration 20 mg/dm³

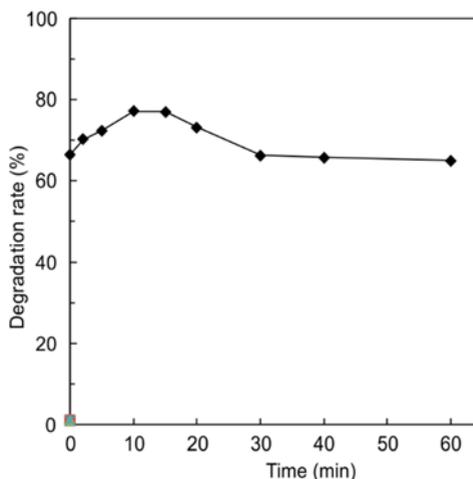


Fig. 8. Time dependences of the DMP photodegradation rate for WO₃/TNAs photoelectrodes fabricated at Na₂WO₄ concentration of 0.01 mol/dm³, deposition potential 3 V, annealing temperature 550 °C, initial DMP concentration 20 mg/dm³

Figure 7 presents the photodegradation rates of DMP for WO₃/TNAs photoelectrodes fabricated at various Na₂WO₄ concentrations. The degradation rate of DMP increased when the concentration of Na₂WO₄ increased at the range of 0–0.01 mol/dm³. The photodegradation rate decreased when the concentration of Na₂WO₄ exceeded 0.01 mol/dm³. This agreed with previous experiments (Fig. 6) which showed that redundant WO₃ became the recombination centers of photogenerated electron-hole pairs and inhibited the light absorption of TNAs. Therefore, superfluous WO₃ would undermine the photodegradation rate of DMP for WO₃/TNAs photoelectrode.

Figure 8 shows the photodegradation rates of DMP for WO₃/TNAs photoelectrodes fabricated at various deposition times. The results indicated that the photodegradation rates of DMP increased with the deposition time when the time was shorter than 10 min. When the deposition time was over 15 min, the photodegradation rate of DMP decreased. This could be attributed to the excessive WO₃ sediment on the surface of TNAs

(Fig. 4), which inhibited the light absorption and the transfer of photogenerated carriers. The results were similar to those presented in Figs. 6 and 7.

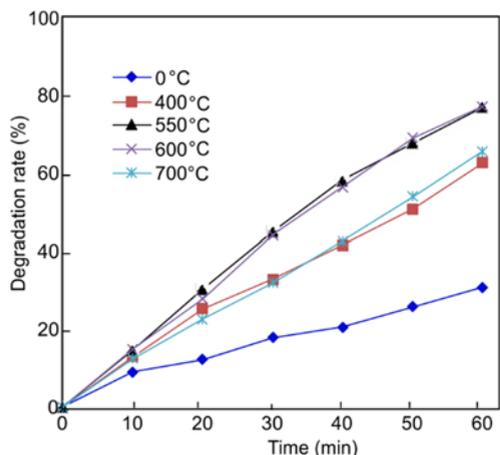


Fig. 9. Time dependences of the DMP photodegradation rate for WO_3/TNAs photoelectrodes fabricated at various annealing temperatures at Na_2WO_4 concentration of 0.01 mol/dm^3 , deposition time 10 min, deposition potential 3 V. The initial DMP concentration was 20 mg/dm^3

The photodegradation rates of DMP for WO_3/TNAs photoelectrodes fabricated at various annealing temperatures are shown in Fig. 9. WO_3/TNAs photoelectrode without calcination displayed the lowest photodegradation rate of DMP after 60 min of illumination. The photodegradation rates of DMP for WO_3/TNAs photoelectrodes annealed at 400, 550, 600, and 700 °C reached 62.7, 77.1, 77.2 and 65.7%, respectively. The results verified that the WO_3/TNAs photoelectrode annealed at 550 and 600 °C performed excellent photocatalytic activity. The optimum photocatalytic performance was ascribed to the mixed crystal effect, which promoted the separation of photogenerated carriers [12, 26]. When the annealing temperature was 700 °C, the photodegradation rate of DMP decreased due to the collapse of nanotube array (Fig. 5e). The decrease caused the reduction of the specific surface area and was detrimental to the transfer of photogenerated electrons.

3.3. PHOTOCATALYTIC STABILITY OF WO_3/TNAs PHOTOELECTRODES

The stability of WO_3/TNAs photoelectrode is a significant indicator for evaluation of its practical application. In order to evaluate the stability of WO_3/TNAs photoelectrode, the degradation efficiency of DMP was investigated by recycling the photoelectrodes for 10 cycles under irradiation for 60 min in each cycle. The stability and reusability of the WO_3/TNAs photoelectrodes is shown in Fig. 10. The removal efficiency of DMP was above 76% for all cycles. The experimental results indicated excellent chemical stability of WO_3/TNAs photoelectrodes, which could be ascribed to the formation of a robust coupling structure between WO_3 and the TNAs.

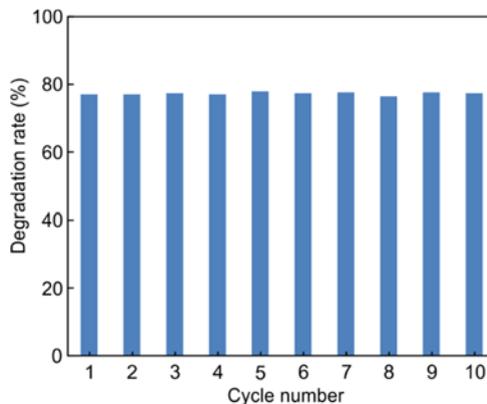


Fig. 10. The evolution of DMP photodegradation rate with the photodegradation cycles for WO₃/TNAs photoelectrodes fabricated at Na₂WO₄ concentration of 0.01 mol/dm³, deposition time 10 min, deposition potential 3 V, annealing temperature 550 °C, initial DMP concentration 20 mg/dm³, and 60 min illumination time for each cycle

4. CONCLUSIONS

Various WO₃/TNAs photoelectrodes were fabricated by the electrodeposition method on TNAs substrate. The results showed that suitable amount of WO₃ could improve the photocatalytic activity of TNAs photoelectrode. Under the 3.0 V deposition potential, 10 min deposition time, 0.01 mol/dm³ Na₂WO₄, and 550 °C annealing temperature, the optimum photocatalytic performance of WO₃/TNAs photoelectrode was achieved and the photodegradation rate of DMP reached 77% after 60 min of illumination. After re-using the WO₃/TNA photoelectrodes 10 times, the photodegradation rate was still over 76%. The enhancement of photocatalytic performance by incorporating WO₃ onto TNAs would provide a theoretical basis for the practical application of WO₃/TNA photoelectrodes in water treatment.

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