International Journal of ELECTROCHEMICAL SCIENCE www.electrochemsci.org

Short Communication

# Electrochemical Study and Synthesis of Highly-ordered TiO<sub>2</sub> Nanorods Arrays on 3D Graphene Oxide Framework as Photocatalyst for Acid Orange 7 Degradation

Zhiyong Wang<sup>1,\*</sup>, Aijiang He<sup>2</sup>, Lixiu Liu<sup>2,\*</sup>

 <sup>1</sup> Department of Basic course, Shenyang University of Technology, Liaoyang, 111003, Liaoning, China.
<sup>2</sup> School of New Materials and Chemical Energy, YiBin Vocational And Technical College, Yibin 644003, China

\*E-mail: weeklywang@163.com, Liulixiu2020@163.com

Received: 4 March 2022 / Accepted: 11 April 2022 / Published: 7 May 2022

The current research focused on the hydrothermal synthesis of highly-ordered TiO<sub>2</sub> nanorods arrays on a 3D graphene oxide framework (TiO<sub>2</sub> NRs/3D-GO) and the photocatalytic performance of the TiO<sub>2</sub> NRs/3D-GO in the decolorization of Acid orange 7 (AO7) from textile wastewater in the presence of UV light. The results of structural investigations revealed that TiO<sub>2</sub> NRs arrays were anchored on wrinkles of 3D-GO nanosheets, resulting in a porous surface with multiple active sites. Optical tests revealed that the band gap values of TiO2 NRs and TiO2 NRs/3D-GO were 3.11 and 3.09 eV, respectively, and that the addition of GO to TiO2 resulted in a noticeable increase in light absorption and made photo-excitation of charge carriers with low energy easier. In comparison to TiO<sub>2</sub> NRs, EIS studies showed that TiO2 NRs/3D-GO had a higher charge carrier transfer rate and lower charge recombination. Results of photocatalytic analyses demonstrated that the total decolorization of 100 ml of 150 mg/l AO7 had been acquired after 160 and 140 minutes of UV light illumination for TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO, respectively, which revealed the efficient photocatalytic activity of TiO<sub>2</sub> NRs/3D-GO compared to reported photocatalysts in the literature for degradation of AO7 because of the synergetic effect of 3D-GO and TiO<sub>2</sub> NRs, and efficient separation of the electron-hole pairs due to the formation of chemical bonding as an intermediate band in the energy band gap of TiO<sub>2</sub> NRs/3D-GO. Furthermore, the results showed that both TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO had the potential to photodegrade AO7 from textile effluent.

**Keywords:** TiO<sub>2</sub> nanorods; 3D graphene oxide framework; Hydrothermal; Acid orange 7; Decolorization; Electrochemical impedance spectroscopy

# **1. INTRODUCTION**

Acid orange 7 (AO7; sodium; 4-[(2-hydroxynaphthalen-1-yl) diazenyl]benzenesulfonate) is a non-reactive azo dye also known as 2-naphthalen-1-yl]benzenesulfonate [1-3]. AO7 is a low-cost indicator pollutant that dyes quickly in weak acidic solutions [4]. As a result, synthetic fibers, nylon, aluminum, leather, detergents, cosmetics, linen, wool, cotton, and silk are all dyed using it in the paper, textile, and tannery industries [5-7]. In general, AO7 like most other azo dyes can be introduced in industrial wastewater, transported along both aquatic and terrestrial pathways. As a consequence it can enter the food chain and cause health risks to organisms and humans [8-10].

AO7 develops an electron shortage and acts as a reducing agent of carcinogenic amino compounds [11, 12]. As a result, the high toxicity and probable carcinogenic characteristics of AO7 are currently a major source of worry [13-15]. Furthermore, it might lead to anemia, headaches, dizziness, skin irritation, and nausea [16-18].

As a result, wastewater treatment technologies must advance in order to effectively remove dye content from effluents prior to disposal [19-21]. As a result, many studies have been focused on the decolorization of dye-contaminated wastewater using biological, physical, and chemical degradation techniques such as adsorption, flotation, coagulation, electrolysis, oxidation, reduction, filtration, ion exchange, ultrasonic mineralization, and photocatalysis [22-24]. Photocatalysis, an affordable and environmentally acceptable treatment technology for the degradation of numerous types of organic and inorganic pollutants in wastewaters [25-27], is one of these procedures for the decolorization of azo dyes [28-30].

Recently, heterogeneous photocatalysis using semiconductors such as TiO<sub>2</sub> has piqued the interest of many researchers as a promising material for photodegradation processes due to its abundance, optical-electronic properties, biocompatibility, low cost, exceptional chemical stability, and nontoxicity [31-33]. However, pristine TiO<sub>2</sub> still suffers from the limitations of low utilization of visible light and a rapid photogenerated charge carrier recombination rate [34-36]. Thus, many studies have been conducted on modification and hybridization of TiO<sub>2</sub> photocatalysts to enhance the light absorption capability and reduce the recombination rate of photogenerated charge carriers [25-27, 31, 34, 37]. Therefore, the present study has been conducted on the hydrothermal synthesis and characterization of TiO<sub>2</sub> NRs/3D-GO and its application to the photocatalytic decolorization of AO7 from textile wastewater in the dark and the presence of UV light illumination.

## 2. EXPERIMENTAL

## 2.1. Synthesize Highly-ordered TiO<sub>2</sub> nanorods arrays on 3D graphene framework

To prepare the TiO<sub>2</sub> NRs/GO framework, 1 g TiO<sub>2</sub> powder (99% anatase, Sigma-Aldrich) and 0.3 g L-Ascorbic acid (99%, Sigma-Aldrich) were ultrasonically disseminated in 20 ml of deionized water for 20 minutes using the hydrothermal technique [38]. Following that, 20 mL of 10 g/L GO (99%, Xiamen Tob New Energy Technology Co., Ltd., China) suspension was ultrasonically added to the produced mixture, and ultrasonication was maintained for 20 minutes to achieve a homogeneous brown suspension. The resulting suspension was then placed in an oven and baked at 110°C for 150

minutes to produce a black TiO2 NRs/GO hydrogel. After cooling, the product was immersed in 50 ml of 10 M NaOH (99.0%, Xiamen Tob New Energy Technology Co., Ltd., China) and transferred to a Teflon-lined stainless autoclave, where it was heated for 24 hours at 160 °C. After cooling, the product was washed with deionized water and 0.04 M HCl ( $\geq$ 99%, Sigma-Aldrich) solution followed by drying at room temperature. The resulting composite was then heat treated for 5 hours in a tube furnace with 225 sccm of N<sub>2</sub> flowing at 400 °C. Finally, highly-ordered TiO<sub>2</sub> nanorod arrays on a 3D graphene framework could be obtained.

#### 2.2. Characterization

The crystalline structures of TiO<sub>2</sub> NRs, GO and TiO<sub>2</sub> NRs/GO were investigated by X-ray diffraction (XRD, Rigaku D/max 2500, Japan). The morphology and structure of the nanostructures were studied by scanning electron microscopy (SEM, Hitachi S-4800, Japan). The optical properties of samples were studied using a UV–Visible spectrophotometer (Cary 5000, Varian, Inc., Palo Alto, CA). The electrochemical impedance spectroscopy (EIS) measurements were performed by an electrochemical workstation (CHI760E, Shanghai) in a 0.5 M Na<sub>2</sub>SO<sub>4</sub> solution by applying an AC voltage of 10 mV in the frequency range from 10 mHz to 10 kHz at open circuit. ZView software was used to fit the electrical circuit with EIS data. A drop of 0.5 g/l of synthesized nanostructures was dropped on the ITO glass, which is used as a working electrode for EIS experiments. A saturated Ag/AgCl electrode and Pt wire were used as a reference electrode and counter electrode, respectively.

# 2.3. Evaluation of photocatalytic activity

The photocatalytic activity of the TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO was determined by measuring the rate of decolorization of AO7 solution in the presence of UV light illumination. A 0.2 g photocatalyst was suspended in 100 ml of 150 mg/l AO7 solution and a UV lamp (3.3W, 385nm, Shenzhen Heyi Optical Control Co., Ltd., China) as a light source was kept at a distance of 8 cm from the reaction vessel. Before the illumination, the suspension was magnetically stirred in the dark for one hour to achieve adsorption desorption equilibrium. During the UV light illumination, the suspension was magnetically stirred at a given time interval, and then, the illuminated suspension was withdrawn using a disposable syringe and filtered through a filter membrane (0.2  $\mu$ m, Hangzhou Kosma Membrane Technology Co., Ltd., China). Variations in the concentration of illuminated AO7 solutions were monitored using a spectrophotometer (E-1000UV31, PEAK Instruments (Shanghai) Co., Ltd., China) at  $\lambda = 484$  nm [37, 39]. The percentage of degradation efficiency or decolorization efficiency was calculated from the following equation [40, 41]:

Degradation efficiency (%) =  $\frac{A_0 - A_t}{A_0} \times 100 = \frac{C_0 - C_t}{C_0} \times 100$ 

Where  $A_0$ ,  $C_o$  and  $A_t$ ,  $C_t$  are the absorbance and corresponded concentration of the AO7 dye at initial time and time t at the  $\lambda_{max}$ , respectively.

## **3. RESULTS AND DISCUSSION**

#### 3.1. XRD and SEM results

The XRD patterns of TiO<sub>2</sub> NRs, 3D-GO, and TiO2 NRs/3D-GO are shown in Figure 1. The XRD pattern of 3D-GO shows a prominent diffraction peak at  $2 = 10.15^{\circ}$ , which corresponds to the GO (001) plane [42, 43]. Diffraction peaks at  $2 = 25.19^{\circ}$ ,  $36.95^{\circ}$ ,  $47.79^{\circ}$ ,  $53.67^{\circ}$ ,  $54.79^{\circ}$ ,  $62.48^{\circ}$ ,  $68.78^{\circ}$ , 70.04°, and 74.96°, respectively, are assigned to the (101), (004), (200), (105), (211), (213), (116), (220), and (215) planes of the TiO<sub>2</sub> anatase phase, as shown in XRD patterns (JCPDS card no. 21-1272) [44, 45]. The XRD pattern of TiO<sub>2</sub> NRs/3D-GO shows all anatase TiO<sub>2</sub> and GO diffraction peaks, indicating that the TiO<sub>2</sub> NRs/3D-GO was effectively synthesized utilizing the hydrothermal process.



Figure 1. The XRD patterns of TiO<sub>2</sub> NRs, 3D-GO and TiO<sub>2</sub> NRs/3D-GO.

Figure 2 shows SEM images of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO, respectively. Figure 2a shows TiO2 NRs generated in a perfect rod shape with an average length and diameter of 180 and 50 nm, respectively, as seen by SEM. Figure 2b shows that after hydrothermal processing, highly-ordered TiO<sub>2</sub> NRs arrays with an average length of 200 nm and a diameter of 30 nm are uniformly and densely distributed on the 3D-GO framework, implying that 3D-GO could be an appropriate substrate for the formation of highly-ordered TiO<sub>2</sub> NRs arrays. Anchoring TiO<sub>2</sub> NRs arrays on wrinkles of 3D-GO nanosheets is clearly evident in SEM images of TiO<sub>2</sub> NRs/3D-GO, forming a porous surface with multiple active sites that increases the effective surface area.

Figure 2. SEM images of (a) TiO<sub>2</sub> NRs, (b) TiO<sub>2</sub> NRs/3D-GO.

# 3.2. Results of optical study

The optical absorbance spectra of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO are shown in Figure 3s. Both samples show substantial absorption bands in the UV region, which can be attributed to anatase TiO<sub>2</sub> intrinsic band gap absorption and electrons stimulated from the valence band to the conduction band [46-48]. It is seen that the addition of GO to TiO<sub>2</sub> by the present method resulted in a noticeably enhanced absorbance, which is evident in the enhancement in photo-absorptions in a UV light regions compared with the pure TiO<sub>2</sub> NRs. It is also accompanied by red-shifting of the absorption edge for TiO<sub>2</sub> NRs/3D-GO which is attributed to the narrowing of the optical band gap energy by the chemical bonding such as e Ti -C bond between TiO<sub>2</sub> NRs and GO [49-51]. Because of the dimensionality, anchoring TiO<sub>2</sub> NRs on nanosheets of 3D-GO could boost electron transit and reinforce the electrical characteristics of GO, which is linked to increased light absorption and a lower recombination rate of photo-generated electron-hole pairs. GO not only creates a large specific surface area and hence improves photocatalytic activity, but it also provides an efficient rapid electron transport channel [52-54]. Figure 3b shows the Tauc plot of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO, which is used to estimate the optical band gap value of samples through the following equation [55, 56]:

$$(\alpha h\nu)^2 = A(h\nu - E) \qquad (2)$$

where  $\alpha$  is the absorption coefficient, h is the Planck's constant (6.6260755 × 10<sup>-34</sup> J·s), v is photon frequency, A is the is proportionality constant, and E is the optical band gap. Extrapolating the linear section of the curves until they intersect the photon energy (hv) axis in Figure 3 yields the band gap value.



**Figure 3.** (a) UV-visible absorption spectra and (b) plot of  $(\alpha hv)^2$  vs. hv for determination band gap energy value of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO.

The band gap values for  $TiO_2$  NRs and  $TiO_2$  NRs/3D-GO are determined to be 3.11 and 3.09 eV, respectively. Reduced band gap energy in  $TiO_2$  NRs/3D-GO indicates easier photo-excitation of charge carriers with low energy, resulting in more electron and hole pairs and improved photocatalytic treatment of dyes.

#### 3.3. Electrochemical study

EIS measurements were performed in a 0.5 M Na<sub>2</sub>SO<sub>4</sub> solution to evaluate the electronic transfer properties of photocatalysts by applying a 10 mV AC voltage in the frequency range of 10 mHz to 10 kHz at open circuit. The Nyquist plots of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO are shown in Figure 4a, which shows the features of deformed semicircle curves. The charge transfer resistance at the interface is proportional to the radius of the semicircle. As can be shown, TiO<sub>2</sub> NRs/3D-GO has a smaller semicircle radius than TiO<sub>2</sub> NRs, indicating that TiO<sub>2</sub> NRs/3D-GO has a reduced charge transfer resistance [57, 58]. Figure 4b depicts the obtained Bode plots of TiO<sub>2</sub> NRs and TiO2 NRs/3D-GO which contained one obvious phase angle peak, which corresponded to one constant time and indicated to the electron transfer processes occurred at the electrode/electrolyte interface [59, 60]. The equivalent circuit fitting model of Nyquist plots is shown in Figure 4a and the results of fitting parameters are presented in Table 1 which consists of Rs as the solution resistance, Rct as charge transfer resistance and  $C_{DL}$  (Q) as a constant phase element attributed to the double-layer capacitance and the separation of the charge carriers at the interface of the working electrode surface [61, 62]. In Q instead of the double layer capacitor, in order to take into account the depression of the capacitive loop [63]. The impedance of  $C_{DL}$  (Z<sub>Q</sub>) as frequency dependent parameter can be determined by the following equation [64, 65]:

$$Z_{Q} = \frac{1}{Q_{0} (j\omega)^{n}}$$
(3)

Where,  $j = (-1)^{1/2}$  is an imaginary number,  $Q_0$  defines the constant representative for CPE  $(\Omega^{-1}cm^{-2}s^n)$ ,  $\omega = 2\pi v$  and v represent the angular frequency and frequency, respectively. The factor n is an adjustable parameter that usually lies between 0 and 1, when n=0 and 1 correspond to a pure resistor and a pure capacitor, respectively, and n=0.5 corresponds to Warburg type impedance [66, 67]. The summarized results in Table 2 show that TiO<sub>2</sub> NRs/3D-GO has higher value of the C<sub>DL</sub> and a lower value of Rct, indicating enhanced charge carrier transfer rate and decreased charge recombination in TiO<sub>2</sub> NRs/3D-GO compared to TiO<sub>2</sub> NRs.



**Figure 4.** (a) Nyquist plots (inset: used equivalent circuit) and (b) bode plots for TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO.

Sample	Rs(Ω)	$C_{dl} \left( \Omega^{-1} \operatorname{cm}^{-2} S^n \right)$	Rct (kΩ)	n
TiO <sub>2</sub> NRs	8.80	1.49	3.811	0.921
TiO <sub>2</sub> NRs/3D-GO	9.19	1.50	3.491	0.923

Table 1. Values of the equivalent elements.

## 3.4. Analysis the photocatalytic activity

Figure 5 shows the degradation efficiency of a blank sample,  $TiO_2$  NRs, and  $TiO_2$  NRs/3D-GO in the presence of UV radiation and 100 ml of 150 mg/l AO7 solution in the dark. The degradation efficiency in the dark for all samples is determined to be 0.76% in the first 40 minutes, and then remains stable for the next 20 minutes in the dark, indicating that the adsorption and desorption processes of AO7 molecules on the photocatalyst surface have reached equilibrium [68-70]. Additionally, the degradation efficiency of a blank sample was obtained ~ 1.91% after 3 hours of UV light illumination. However, Figure 5a reveals noteworthy decolorization in the first 5 minutes of UV light illumination for both photocatalysts such that the degradation efficiency is attained at 15% and

18% on  $TiO_2$  NRs and  $TiO_2$  NRs/3D-GO, respectively. Thus, UV light and the presence of photocatalyst have been recognized to play an important role in the photocatalytic decolorization of AO7.

Furthermore, after one hour of UV light exposure, the degradation efficiency of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO was found to be 70% and 86.5 percent, respectively. Total decolorization was achieved for TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO, respectively, after 160 and 140 minutes of UV light exposure. According to the SEM data, TiO<sub>2</sub> NRs/3D-GO has a higher rate of AO7 degradation due to its large surface area and high porosity due to the creation of nanocavities, as well as a higher density of adsorption active sites [71-73]. In addition, the combination of the 3D-GO and TiO<sub>2</sub> NRs facilitates the transfer of a photo-generated electron from TiO<sub>2</sub> to the GO, narrowing the band gap energy of TiO<sub>2</sub> NRs/3D-GO and is a hindrance to the recombination processes of photo-generated electron–hole pairs [55, 74]. It is reported that the presence of carbon nanostructures in TiO<sub>2</sub> based nanocomposites shows improvement in the photo-generated carriers in accordance with the results of optical and EIS analyses [75-77].



**Figure 5.** The degradation efficiency of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO for degradation of 100 ml of 150 mg/l AO7 solution in dark and the presence of UV light.

Table 2.	Comparison	between	photocatalytic	activity	of ph	otocataly	ysts in	n present	study	and	reported
ph	otocatalysts in	n the liter	ratures for deg	radation of	of AO	7.					

Photocatalyst	AO7 content (mg/l)	Light source	Degradation time (minute)	Removal efficienc y (%)	Ref.
g-C <sub>3</sub> N <sub>4</sub> /TiO <sub>2</sub>	5	UV	12	100	[26]
Co-doped TiO <sub>2</sub>	10	visible	180	95.4	[27]
Bi <sub>12</sub> TiO <sub>20</sub>	20	visible	360	90	[25]
TiO <sub>2</sub> supported on Salvinia	20	UV	180	57.6	[78]

molesta biochar					
TiO <sub>2</sub>	30	solar	360	100	[79]
		light			
Pt/TiO <sub>2</sub>	35	UV	30	97	[80]
ZnCrS–O <sub>4</sub>	50	UVA-Vis	120	66	[81]
TiO <sub>2</sub>	50	UV	240	88	[82]
TiO <sub>2</sub>	100	visible	600	100	[83]
TiO <sub>2</sub> NRs	150	UV	160	100	Presen
TiO <sub>2</sub> NRs/3D-GO			140	100	t study

Table 2 shows the comparison between the photocatalytic activity of photocatalysts in the present study and reported photocatalysts in the literature for the degradation of AO7. It is found that efficient photocatalytic activity is obtained for TiO<sub>2</sub> NRs/3D-GO because of the synergetic effect of 3D-GO and TiO<sub>2</sub> NRs, and efficient separation of the electron–hole pairs due to the formation of chemical bonding as an intermediate band in the energy band gap of TiO<sub>2</sub> NRs/3D-GO [84, 85].

Figure 6 exhibits the effect of the initial concentration of AO7 on the photocatalytic activity of  $TiO_2$  NRs/3D-GO. As depicted, the total degradation of 100 ml of 5, 10, 50, 150 and 200 mg/l of AO7 is achieved after 40, 60, 100, 140, and 155 minutes of UV light illumination, respectively. In fixed catalyst content in a photocatalytic reactor, the degradation rate is decreased with the increase of the initial concentration of AO7. It can be related to an insufficient concentration of reactive oxygen species produced during the photocatalytic process, and the absorption of more AO7 molecules on the catalyst surface.



Figure 6. Effect of initial concentration of AO7 (5, 10, 50, 150 and 200 mg/l) on photocatalytic activity of TiO<sub>2</sub> NRs/3D-GO.

The capability of the prepared photocatalysts in the present study was examined for degradation of 100 ml of 150 mg/l AO7 solution, which was prepared using textile wastewater. Figure

7 displays the degradation efficiency of  $TiO_2$  NRs and  $TiO_2$  NRs/3D-GO for degradation of prepared AO7 solution in the presence of UV light, indicating 170 and 148 minutes of total decolorization, respectively. Comparison between findings in Figure 7 and Figure 5 (AO7 solution prepared with deionized water) illustrates the requirement for more time for the total decolorization of AO7 solution prepared of textile wastewater due to the presence of organic and inorganic pollutants. Finally, these observations indicate to the appropriate capability of both  $TiO_2$  NRs and  $TiO_2$  NRs/3D-GO for photodegradation AO7 from textile wastewater.



**Figure 7.** The degradation efficiency of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO for degradation of 100 ml of 150 mg/l AO7 solution prepared using textile wastewater in presence of UV light.

# **4. CONCLUSION**

In summary, this study has been conducted on hydrothermal synthesis, and structural, electrochemical, optical characterizations of TiO<sub>2</sub> NRs/3D-GO and its application to photocatalytic decolorization of 100 ml of 150 mg/l AO7 from textile wastewater in the presence of UV light illumination. Optical studies showed that the addition of GO to TiO<sub>2</sub> resulted in a noticeably enhanced absorbance, which was evident in the enhancement in photo-absorptions in a UV light regions compared with the pure TiO<sub>2</sub> NRs, and it was found that the band gap values of TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO were obtained as 3.11 and 3.09 eV, respectively. EIS studies exhibited that TiO<sub>2</sub> NRs/3D-GO had a higher value of the C<sub>DL</sub> and the lower value of Rct, indicating enhanced charge carrier transfer rate and decreased the charge recombination in TiO<sub>2</sub> NRs/3D-GO compared to TiO<sub>2</sub> NRs. Results of photocatalytic analyses demonstrated that they achieved 70% and 86.5% degradation efficiency after one hour of UV light illumination for TiO<sub>2</sub> NRs and TiO<sub>2</sub> NRs/3D-GO, respectively. The comparison between the photocatalytic activity of photocatalysts in present study and reported photocatalysts in the literature for the degradation of AO7

revealed the efficient photocatalytic activity of  $TiO_2$  NRs/3D-GO because of the synergetic effect of 3D-GO and  $TiO_2$  NRs, and the efficient separation of the electron–hole pairs due to the formation of chemical bonding as an intermediate band in the energy band gap of  $TiO_2$  NRs/3D-GO. Furthermore, results indicated the appropriate capability of both  $TiO_2$  NRs and  $TiO_2$  NRs/3D-GO to photodegradation AO7 from textile wastewater.

# ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by the Chemical and environmental science and technology innovation team (No. ybzy20cxtd03), and the Science and Technology Planning Project of Guangzhou City (No. 202102021061).

# References

- 1. X. Pan, M. Zhang, H. Liu, S. Ouyang, N. Ding and P. Zhang, *Applied Surface Science*, 522 (2020) 146370.
- 2. H. Guan, S. Huang, J. Ding, F. Tian, Q. Xu and J. Zhao, Acta Materialia, 187 (2020) 122.
- 3. H. Maleh, M. Alizadeh, F. Karimi, M. Baghayeri, L. Fu, J. Rouhi, C. Karaman, O. Karaman and R. Boukherroub, *Chemosphere*, (2021) 132928.
- 4. R. Mohamed, J. Rouhi, M.F. Malek and A.S. Ismail, *International Journal of Electrochemical Science*, 11 (2016) 2197.
- 5. A.K.R. Choudhury, Advanced Materials and Technologies for Environmental, 2 (2018) 145.
- 6. L. Zhang, L. Wang, Y. Zhang, D. Wang, J. Guo, M. Zhang and Y. Li, *Environmental research*, 206 (2022) 112629.
- 7. S.-S. Yang, X.-L. Yu, M.-Q. Ding, L. He, G.-L. Cao, L. Zhao, Y. Tao, J.-W. Pang, S.-W. Bai and J. Ding, *Water research*, 189 (2021) 116576.
- 8. W.F. Khalik, L.-N. Ho, S.-A. Ong, Y.-S. Wong, N.A. Yusoff and S.-L. Lee, *Journal of Environmental Health Science and Engineering*, 18 (2020) 769.
- 9. Q. Dai, K. Shen, W. Deng, Y. Cai, J. Yan, J. Wu, L. Guo, R. Liu, X. Wang and W. Zhan, *Environmental Science & Technology*, 55 (2021) 4007.
- 10. T. Gao, C. Li, Y. Zhang, M. Yang, D. Jia, T. Jin, Y. Hou and R. Li, *Tribology International*, 131 (2019) 51.
- 11. S. Yoon, J.J. Calvo and M.C. So, *Crystals*, 9 (2019) 17.
- 12. J.-Z. Cheng, Z.-R. Tan, Y.-Q. Xing, Z.-Q. Shen, Y.-J. Zhang, L.-L. Liu, K. Yang, L. Chen and S.-Y. Liu, *Journal of Materials Chemistry A*, 9 (2021) 5787.
- 13. Z. Zhang, Y. Lou, C. Guo, Q. Jia, Y. Song, J.-Y. Tian, S. Zhang, M. Wang, L. He and M. Du, *Trends in Food Science & Technology*, 118 (2021) 569.
- 14. H. Liu, X. Li, Z. Ma, M. Sun, M. Li, Z. Zhang, L. Zhang, Z. Tang, Y. Yao and B. Huang, *Nano Letters*, 21 (2021)
- 15. S. Guo, C. Li, Y. Zhang, Y. Wang, B. Li, M. Yang, X. Zhang and G. Liu, *Journal of Cleaner Production*, 140 (2017) 1060.
- 16. L. Zhu, G. Liang, C. Guo, M. Xu, M. Wang, C. Wang, Z. Zhang and M. Du, *Food Chemistry*, 366 (2022) 130575.
- 17. H. He, Q.-Q. Zhu, Y. Yan, H.-W. Zhang, Z.-Y. Han, H. Sun, J. Chen, C.-P. Li, Z. Zhang and M. Du, *Applied Catalysis B: Environmental*, 302 (2022) 120840.
- 18. G. Li, S. Huang, N. Zhu, H. Yuan and D. Ge, *Journal of Hazardous Materials*, 403 (2021) 123981.

- 19. J. Liu, T. Li, H. Zhang, W. Zhao, L. Qu, S. Chen and S. Wu, *Materials Today Bio*, (2022) 100243.
- 20. L. Feng, J.J. Liu, Z.C. Guo, T.Y. Pan, J.H. Wu, X.H. Li, B.Z. Liu and H.L. Zheng, *Separation and Purification Technology*, 285 (2021)120314.
- 21. W. Liu, J. Li, J. Zheng, Y. Song, Z. Shi, Z. Lin and L. Chai, *Environmental Science & Technology*, 54 (2020) 11971.
- 22. V.K. Meena, International Journal of Advanced Science and Research, 1 (2016) 58.
- 23. J.-W. Lee, S.-P. Choi, R. Thiruvenkatachari, W.-G. Shim and H. Moon, *Dyes and pigments*, 69 (2006) 196.
- 24. L. Zhang, Y. Xu, H. Liu, Y. Li, S. You, J. Zhao and J. Zhang, *Journal of Water Process* Engineering, 44 (2021) 102368.
- 25. X. Zhu, J. Zhang and F. Chen, *Chemosphere*, 78 (2010) 1350.
- 26. X. Liu, W. Li, R. Hu, Y. Wei, W. Yun, P. Nian, J. Feng and A. Zhang, *Chemosphere*, 249 (2020) 126093.
- 27. K. Hamidian, A. Najafidoust, A. Miri and M. Sarani, *Materials Research Bulletin*, 138 (2021) 111206.
- 28. M. Yang, C. Li, Y. Zhang, D. Jia, R. Li, Y. Hou, H. Cao and J. Wang, *Ceramics International*, 45 (2019) 14908.
- 29. H. Karimi-Maleh, R. Darabi, M. Shabani-Nooshabadi, M. Baghayeri, F. Karimi, J. Rouhi, M. Alizadeh, O. Karaman, Y. Vasseghian and C. Karaman, *Food and Chemical Toxicology*, 162 (2022) 112907.
- 30. N.M. Mohamed, R. Bashiri, F.K. Chong, S. Sufian and S. Kakooei, *international journal of hydrogen energy*, 40 (2015) 14031.
- 31. J. Hu, H. Li, Q. Wu, Y. Zhao and Q. Jiao, *Chemical Engineering Journal*, 263 (2015) 144.
- 32. Y. Liu, Q. Zhang, H. Yuan, K. Luo, J. Li, W. Hu, Z. Pan, M. Xu, S. Xu and I. Levchenko, *Journal of Alloys and Compounds*, 868 (2021) 158723.
- 33. Y.-M. Chu, U. Nazir, M. Sohail, M.M. Selim and J.-R. Lee, *Fractal and Fractional*, 5 (2021) 119.
- 34. Y. Ren, Y. Dong, Y. Feng and J. Xu, *Catalysts*, 8 (2018) 590.
- 35. F. Chen, J. Ma, Y. Zhu, X. Li, H. Yu and Y. Sun, *Journal of Hazardous Materials*, 426 (2022) 128064.
- 36. J. Huo, H. Wei, L. Fu, C. Zhao and C. He, *Chinese Chemical Letters*, (2022) 1.
- 37. S. Silvestri, M.G. Goncalves, P.A. da Silva Veiga, T.T. da Silva Matos, P. Peralta-Zamora and A.S. Mangrich, *Journal of Environmental Chemical Engineering*, 7 (2019) 102879.
- 38. J. Cheng, G. Gu, W. Ni, Q. Guan, Y. Li and B. Wang, *Nanotechnology*, 28 (2017) 305401.
- 39. H. Karimi-Maleh, C. Karaman, O. Karaman, F. Karimi, Y. Vasseghian, L. Fu, M. Baghayeri, J. Rouhi, P. Senthil Kumar and P.-L. Show, *Journal of Nanostructure in Chemistry*, (2022) 1.
- 40. A. Vennela, D. Mangalaraj, N. Muthukumarasamy, S. Agilan and K. Hemalatha, *International Journal of Electrochemical Science*, 14 (2019) 3535.
- 41. T.H. Zhao, M.I. Khan and Y.M. Chu, *Mathematical Methods in the Applied Sciences*, (2021) 1.
- 42. G. Li, J. Wu, H. Jin, Y. Xia, J. Liu, Q. He and D. Chen, *Nanomaterials*, 10 (2020) 307.
- 43. H. Yan, M. Zhao, X. Feng, S. Zhao, X. Zhou, S. Li, M. Zha, F. Meng, X. Chen and Y. Liu, *Angewandte Chemie*, (2022) 1.
- 44. J. Rouhi, S. Kakooei, S.M. Sadeghzadeh, O. Rouhi and R. Karimzadeh, *Journal of Solid State Electrochemistry*, 24 (2020) 1599.
- 45. J. Rouhi, S. Mahmud, S.D. Hutagalung, N. Naderi, S. Kakooei and M.J. Abdullah, *Semiconductor Science and Technology*, 27 (2012) 065001.
- 46. Y. Cong, J. Zhang, F. Chen, M. Anpo and D. He, *The Journal of Physical Chemistry C*, 111 (2007) 10618.

- 47. M. Cao, Z. Chang, J. Tan, X. Wang, P. Zhang, S. Lin, J. Liu and A. Li, ACS Applied Materials & Interfaces, 14 (2022) 13025.
- 48. F. Husairi, J. Rouhi, K. Eswar, C.R. Ooi, M. Rusop and S. Abdullah, *Sensors and Actuators A: Physical*, 236 (2015) 11.
- 49. E. Lee, J.-Y. Hong, H. Kang and J. Jang, *Journal of Hazardous Materials*, 219 (2012) 13.
- 50. G. Yang, X. Feng, W. Wang, Q. OuYang and L. Liu, *Composites Science and Technology*, 213 (2021) 108959.
- 51. B. Huang, L. Changhe, Y. Zhang, D. Wenfeng, Y. Min, Y. Yuying, Z. Han, X. Xuefeng, W. Dazhong and S. Debnath, *Chinese Journal of Aeronautics*, 34 (2021) 1.
- 52. S. Bellamkonda, N. Thangavel, H.Y. Hafeez, B. Neppolian and G. Ranga Rao, *Catalysis Today*, 321-322 (2019) 120.
- 53. J. You, C. Liu, X. Feng, B. Lu, L. Xia and X. Zhuang, *Carbohydrate Polymers*, 288 (2022) 119332.
- 54. N. Naderi, M. Hashim, J. Rouhi and H. Mahmodi, *Materials science in semiconductor* processing, 16 (2013) 542.
- 55. M. Shaban, A.M. Ashraf and M.R. Abukhadra, *Scientific Reports*, 8 (2018) 781.
- 56. M. Nazeer, F. Hussain, M.I. Khan, E.R. El-Zahar, Y.-M. Chu and M. Malik, *Applied Mathematics and Computation*, 420 (2022) 126868.
- 57. H. Shi, Q. Wu, X. Yang, Y. Zuo, H. Yang, R. Zhang, Y. Zhang, Y. Fan, X. Du and L. Jiang, *International Journal of Electrochemical Science*, 16 (2021) 210314.
- 58. H. Wang, J. Cui, Y. Zhao, Z. Li and J. Wang, *Green Chemistry*, 23 (2021) 405.
- 59. D. Qu, G. Wang, J. Kafle, J. Harris, L. Crain, Z. Jin and D. Zheng, *Small Methods*, 2 (2018) 1700342.
- 60. Y. Zhang, H.N. Li, C. Li, C. Huang, H.M. Ali, X. Xu, C. Mao, W. Ding, X. Cui and M. Yang, *Friction*, (2022) 1.
- 61. E. Katz and I. Willner, *Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis*, 15 (2003) 913.
- 62. G. Li, S. Huang, N. Zhu, H. Yuan, D. Ge and Y. Wei, *Chemical Engineering Journal*, 421 (2021) 127852.
- 63. I. Chakib, H. Elmsellem, N. Sebbar, S. Lahmidi, A. Nadeem, E. Essassi, Y. Ouzidan, I. Abdel-Rahman, F. Bentiss and B. Hammouti, *ournal of Materials and Environmental Science*, 7 (2016) 1866.
- 64. L. Jinsong, G. Qian, L. Jing and F. Lin, *International Journal of Electrochemical Science*, 17 (2022) 22027.
- 65. Y.-M. Chu, B. Shankaralingappa, B. Gireesha, F. Alzahrani, M.I. Khan and S.U. Khan, *Applied Mathematics and Computation*, 419 (2022) 126883.
- 66. D. Ge, H. Yuan, J. Xiao and N. Zhu, Science of The Total Environment, 679 (2019) 298.
- 67. J. Rouhi, S. Mahmud, S. Hutagalung and S. Kakooei, *Micro & Nano Letters*, 7 (2012) 325.
- 68. P. Sun, J. Zhang, W. Liu, Q. Wang and W. Cao, *Catalysts*, 8 (2018) 326.
- 69. H. Wang, T. Song, Z. Li, J. Qiu, Y. Zhao, H. Zhang and J. Wang, ACS applied materials & *interfaces*, 13 (2021) 25918.
- 70. C. Xin, L. Changhe, D. Wenfeng, C. Yun, M. Cong, X. Xuefeng, L. Bo, W. Dazhong, H.N. LI and Y. ZHANG, *Chinese Journal of Aeronautics*, (2021) 1.
- 71. S. Cao, B. Fan, Y. Feng, H. Chen, F. Jiang and X. Wang, *Chemical Engineering Journal*, 353 (2018) 147.
- 72. Z. Wang, Q. Lei, Z. Wang, H. Yuan, L. Cao, N. Qin, Z. Lu, J. Xiao and J. Liu, *Chemical Engineering Journal*, 395 (2020) 125180.
- 73. D. Ge, W. Wu, G. Li, Y. Wang, G. Li, Y. Dong, H. Yuan and N. Zhu, *Chemical Engineering Journal*, 437 (2022) 135306.

- 74. B. Li, C. Li, Y. Zhang, Y. Wang, D. Jia and M. Yang, *Chinese Journal of Aeronautics*, 29 (2016) 1084.
- 75. Y. Liang, H. Wang, H. Sanchez Casalongue, Z. Chen and H. Dai, *Nano Research*, 3 (2010) 701.
- 76. Z. Li, H. Li, X. Zhu, Z. Peng, G. Zhang, J. Yang, F. Wang, Y.F. Zhang, L. Sun and R. Wang, *Advanced Science*, (2022)
- 77. K. Eswar, J. Rouhi, H. Husairi, M. Rusop and S. Abdullah, *Advances in Materials Science and Engineering*, 2014 (2014) 1.
- 78. S. Silvestri, M.G. Gonçalves, P.A. da Silva Veiga, T.T.d.S. Matos, P. Peralta-Zamora and A.S. Mangrich, *Journal of Environmental Chemical Engineering*, 7 (2019) 102879.
- 79. S.-A. Ong, O.-M. Min, L.-N. Ho and Y.-S. Wong, *Water, Air, & Soil Pollution*, 223 (2012) 5483.
- 80. G.N. Kryukova, G.A. Zenkovets, A.A. Shutilov, M. Wilde, K. Günther, D. Fassler and K. Richter, *Applied Catalysis B: Environmental*, 71 (2007) 169.
- 81. L. El Mersly, E.M. El Mouchtari, E.M. Moujahid, C. Forano, M. El Haddad, S. Briche, A. Alaoui Tahiri and S. Rafqah, *Journal of Science: Advanced Materials and Devices*, 6 (2021) 118.
- 82. T. Velegraki, I. Poulios, M. Charalabaki, N. Kalogerakis, P. Samaras and D. Mantzavinos, *Applied Catalysis B: Environmental*, 62 (2006) 159.
- 83. M. Stylidi, D.I. Kondarides and X.E. Verykios, *Applied Catalysis B: Environmental*, 47 (2004) 189.
- 84. N. Wan, Z. Xing, J. Kuang, Z. Li, J. Yin, Q. Zhu and W. Zhou, *Applied Surface Science*, 457 (2018) 287.
- 85. L. He, C. Yang, J. Ding, M.-Y. Lu, C.-X. Chen, G.-Y. Wang, J.-Q. Jiang, L. Ding, G.-S. Liu and N.-Q. Ren, *Applied Catalysis B: Environmental*, 303 (2022) 120880.

© 2022 The Authors. Published by ESG (<u>www.electrochemsci.org</u>). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).