Glass fiber supported BiOI thin-film fixed-bed photocatalytic reactor for water decontamination under solar light irradiation

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ABSTRACT

BiOI powder has been proved to be an efficient photocatalyst, but the difficulty in removing it from water after reaction limits its application in real water treatment. To solve this problem, a thin-film fixed-bed reactor (TFFBR) was set-up by developing a BiOI thin film on glass fiber cloth (GFC). The composition and structure of the as-prepared films were characterized with X-ray diffraction, X-ray photoelectron spectroscopy, field emission microscopy, transmission electron microscopy and Fourier transform infrared spectroscopy. The BiOI thin film was made by painting a silica sol containing BiOI on GFC, which could be tailored to desired sizes to accommodate the TFFBR. The mass of BiOI on the GFC increased with the number of iterations of the painting process. SiO2 sol glued the BiOI particles tightly onto the GFC, making the thin film strong enough to resist fluid flushing in the TFFBR. The photocatalytic activity of the BiOI thin film was investigated by degrading bisphenol A (BPA) under simulated sunlight. Ninety eight percent of BPA (20 mg/L in 2 L) was degraded by the BiOI thin film sample of seven layers (GFC-7) on the TFFBR within 8 hr irradiation. The GFC-7 displayed good photocatalytic ability toward artificial sewage containing BPA in a wide pH range (5–9), and also demonstrated excellent durability and reusability. The working conditions were optimized and it was found that the thickness of the fluid film and residence time over the thin film were key factors affecting the photocatalytic efficiency.

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Introduction

Environmental pollution is becoming one of the major challenges in the twenty-first century, especially for the aquatic environment, which is contaminated by a variety of emerging organic contaminants (Rodriguez-Narvaez et al., 2017). Among the available biological, physical and chemical treatment techniques, photocatalytic remediation driven by solar light has received intensive interest since it has the advantages of being energy-saving and generating little or no secondary contaminants (Malato et al., 2009, 2016). As members of the class of visible-light-driven photocatalysts, bismuth oxyhalides (BiOX, X=Cl, Br, I) display superior photocatalytic activity (Cheng et al., 2014; Zhang et al., 2018b). The excellent visible photo-response properties of BiOX are attributed to their outstanding optical and electrical properties (Ye et al., 2017).

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BiOBr@SiO2, indicated that the catalytic activity of TiO2 or application of photocatalysts in water treatment. Although than the original activity (Wang et al., 2018; Yuan et al., 2016). BiOBr was not apparently affected by SiO2, or was even higher which could be used for building a solar-light-driven photo-irradiation (Abdel-Maksoud et al., 2016; Jafarikojour et al., 2015; McCullagh et al., 2011; Tugaoen et al., 2018). However, there are very few reports on preparation of BiOX thin films, which could be used for building a solar-light-driven photocatalytic reactor for real water decontamination.

To build up TiO2 thin-film-based UV-light driven reactors, various substrates such as glass plates (Cui et al., 2017; Mehrjouei et al., 2013; Vella et al., 2010; Ye et al., 2013), quartz fibers (Jia et al., 2015; Kim et al., 2012), glass beads (Chiou et al., 2006; Shen et al., 2012), stainless steel (Momeni et al., 2017; Wang et al., 2017; Yu et al., 2003) and glass fibers (Erjavec et al., 2016; Zazhigalov et al., 2017) have been used as supporting substrates. Among them, glass fiber cloth (GFC) is particularly promising due to its special characteristics, such as low cost, good light transmittance, flexibility, corrosion resistance, large surface area and adaptability (being easily cut into desired sizes) (Erjavec et al., 2016; Jafarikojour et al., 2015). Various methods including chemical vapor transport (Starr et al., 2016; Ye et al., 2013; Ye and Chen, 2016), electrodeposition methods (Cruz-Ortiz et al., 2016; Hachisu et al., 2016) and sol-gel methods (Mohamed et al., 2017; Zhou et al., 2017), have been developed to prepare substrate-supported photocatalytic thin films. Among these methods, the sol-gel method has found wide application since it does not require expensive equipment or complicated operations (Yuan et al., 2016).

In recent years, some efforts have been made to immobilize BiOX on the surface of supporting substrates such as glass and cement using direct coating or sol-gel silica coating methods (Cui et al., 2017; Jia et al., 2015; Shen et al., 2015; Wang et al., 2018). Direct coating followed by calcination is not suitable for preparation of a film in a large-scale reactor. A sol-gel coating with silica as an adhesion agent might be a noteworthy choice for BiOX thin-film preparation (Shen et al., 2015; Wang et al., 2018; Yuan et al., 2016). Previous reports on composite catalysts containing SiO2, such as TiO2@SiO2 and BiOBr@SiO2, indicated that the catalytic activity of TiO2 or BiOBr was not apparently affected by SiO2, or was even higher than the original activity (Wang et al., 2018; Yuan et al., 2016).

Developing photocatalytic reactors is the key to large-scale application of photocatalysts in water treatment. Although many excellent photocatalysts have been fabricated, there is a large gap between laboratory studies and application of these photocatalysts in real-water treatment systems to eliminate pollutants. At present, the photocatalytic reactors mainly include the parabolic trough solar reactor (Hong et al., 2012), double skin sheet reactor (Braham and Harris, 2009) and thin-film fixed-bed reactor (TFFBR) (Braham and Harris, 2009; Zayani et al., 2009). The TFFBR has the advantages of simple structure, convenient operation and low cost. In addition, the TFFBR has a high utilization rate of light, and favors transfer of oxygen to the liquid film efficiently (Braham and Harris, 2009; Khan et al., 2012; Zayani et al., 2009).

In this study, BiOI thin films on GFC were fabricated by a sol-gel method. The obtained films were characterized and applied in a TFFBR for water treatment under simulated solar light irradiation. Bisphenol A (BPA) is regarded as an endocrine disrupting compound and can cause negative effects on immune, reproductive and nerve systems. Thus, BPA was chosen as model pollutant for evaluating the decontamination efficiency of the reactor (Huang et al., 2012; Krishnan et al., 1993). To evaluate the application in real-water treatment, artificial sewage containing BPA was prepared, and the durability and reusability of the films were evaluated.

1. Experimental
1.1. Materials and reagents

Bisphenol A (BPA, 98%) was purchased from Aladdin Industrial Corporation (Shanghai, China). Bismuth nitrate pentahydrate (Bi(NO3)3•5H2O), potassium iodide (KI), tetraethylorthosilicate (TEOS) and other conventional reagents were all analytical grade and obtained from native chemical reagent companies. Glass fiber cloth (GFC, alkali-free, 200 g/m2) was purchased from Japan East Electrician Ltd. (Suzhou, China). Deionized water was used throughout all experiments.

1.2. Synthesis of BiOI thin films on GFC

The silica coating of BiOI was carried out using a sol-gel method by mixing the as-prepared BiOI powder with silica sol. Five mL of TEOS was dissolved in 2.6 mL of ethanol, and then vigorously stirred for 0.5 hr. Afterwards, 1.7 mL of 0.7 mol/L HCl was added (Jia et al., 2015), followed by refluxing at 78°C for 13 min, which resulted in SiO2 sol. Subsequently, 2.0 g of BiO powder, which was prepared using a solvothermal method described in a previous report (Chang et al., 2013), was thoroughly dispersed in the mixture of freshly prepared SiO2 sol (1.5 mL) and ethanol (30 mL). The mixture was stirred magnetically for 1 hr to obtain a uniform suspension.

The GFC was pretreated by a sintering method (Sangkhun et al., 2012) to remove impurities. The prepared suspension was evenly painted onto the sintered GFC using a soft brush. The coated cloth was dried in an oven at 100°C for 1 hr, and the obtained thin film sample was named as GFC-1. This process was repeated several times to get GFC-3, -5 and -7, where the number represents the layers of BiOI on the cloth. The immobilized BiOI of GFC-7 was scraped off, which was
named as BiOI-7, and was subjected to further characterization. The coated GFCs were cut into pieces of 3 × 15 cm and 25 × 30 cm to investigate their photocatalytic activity in the photochemical reactor.

1.3. Characterization of the BiOI powder and as-prepared films

The X-ray diffraction patterns (XRD) were obtained on a D/MAX 2500V diffractometer (Rigaku, Japan) with Cu Ka radiation to obtain the crystal structure of the samples. The morphologies of the samples were observed using a field emission scanning electron microscope (FESEM, LEO, Germany) and a transmission electron microscope (TEM, JEM-2100FEF, JEOL, Japan). X-ray photoelectron spectroscopy (XPS, Axis Ultra DLD, Kratos, Japan) was performed to confirm the elemental compositions and chemical states of the materials. The Fourier transform infrared (FT-IR) spectra were obtained on a MAGNA-560 Infrared Spectrometer (Nicolet, USA). Photocurrent measurement was performed on a CHI 600D electrochemical system (Chenhua Instruments Co., Shanghai, China) (Cui et al., 2017). The photoluminescence (PL) spectra for solid samples were obtained on a FP-8500 fluorescence spectrophotometer (Jasco, Japan) with an excitation wavelength of 320 nm. The surface areas were obtained using the Brunauer–Emmett–Teller (BET) method, and the average pore diameter was obtained from the sorption/desorption isotherms of N2 using the Barrett–Joyner–Halenda (BJH) equation on data obtained by a surface area and porosimetry analyzer (TriStar 3000, Micromeritics, USA). A UV–Vis spectrometer (U-3010, Hitachi, Japan) in the range of 200–800 nm was used to measure UV–Vis diffuse reflectance spectra (DRS) of the samples. The band gap of the as-prepared catalysts was calculated using the following equation (Ma et al., 2012): 

\[ \alpha h v = A (h v - E_g)^{n/2} \]

where \( \alpha \) is the absorption coefficient, \( h \) is Planck constant, \( v \) is the photon frequency, and \( E_g \) is the semiconductor band gap energy, respectively, and \( A \) is a constant. The parameter \( n \) depends on the type of transition, with \( n = 1 \) for a direct transition and \( n = 4 \) for an indirect transition. For BiOI, \( n \) was 4 (Zhang et al., 2018a).

1.4. Photocatalytic test and BPA analysis

The photocatalytic activity of the as-prepared BiOI thin films and the scraped BiOI-7 powder was evaluated on an XPA-7 photochemical reactor (Xujiang Electromechanical Plant, Nanjing, China). An 800 W Xe lamp was used as light source. The prepared BiOI thin films (3 × 15 cm) were vertically placed in quartz tubes containing 40 mL of BPA (20 mg/L). For comparison, 20 mg of pure BiOI powder was added in one of the tubes containing 40 mL of BPA (20 mg/L). Before irradiation, the suspensions were stirred in the dark for 1 hr to establish adsorption–desorption equilibrium. At certain time intervals, 1 mL of solution was taken out and centrifuged at 10,000 r/min. The supernatant was sampled and analyzed on a High-Performance Liquid Chromatograph (HPLC, Agilent 1260 Infinity, Agilent Corporation, USA) with a Fluorescence Detector. More detailed instrumental conditions are provided in Appendix A. The stability of the as-prepared thin-film GFC-7 was tested through a recycling test.

1.5. Photocatalytic activity evaluation of the TFFBR

A thin-film fixed-bed reactor (TFFBR) was set-up, consisting of a peristaltic pump, two reservoirs, a light source and a sloping plate for supporting the film and collecting light (Fig. 1), according to a previous design with minor modifications (Khan et al., 2012; Sudrajat and Babel, 2016). The BiOI thin-film with a working area of 25 × 30 cm was attached on the sloping plate. At the top of the sloping plate, there was a water buffer zone with a splitter, which guaranteed that the reaction solution flowed over the immobilized film smoothly and evenly. The BPA (20 mg/L) solution in a reservoir of 2.5 L was pumped by a peristaltic pump to the top buffer zone through the splitter, and flowed along the sloping plate as a fluid film. The slope of the plate and the flow rate were adjustable. The position of an 800 W Xe lamp was adjusted to make sure the films were perpendicular to the light source at a 10 cm distance. After a given irradiation time, an aliquot of the solution was sampled and analyzed by HPLC. In order to make the experiment more realistic, 2 L of artificial sewage was used and analyzed by HPLC. In order to make the experiment more realistic, 2 L of artificial sewage (Chen et al., 1995) containing BPA (20 mg/L) was used throughout the reactor tests. The pH of the solution was adjusted to the desired level using diluted NaOH and HCl. The reusability of the TFFBR with BiOI-7 thin film was evaluated by running it for 12 cycles. Thereafter, the GFC-7 was dried and kept in the dark at room temperature for 6 months. Then, it was used for a degradation experiment to evaluate the stability of the GFC-7.

2. Results and discussion

2.1. Characterization of the BiOI thin film

As shown in Fig. 2, the XRD patterns of pure BiOI and BiOI-7 were similar to each other, and were well indexed to the pure phase of tetragonal BiOI (JCPDS file No. 10-0445) with good
crystallinity (Liu et al., 2012; Zhang et al., 2018a). This suggested that mixing with SiO2 sol during the thin-film preparation did not evidently affect the crystal phase of BiOI. The broad diffraction peak of SiO2 at ca. 23° was not detected due to its low weight ratio (<3.0%) (Yuan et al., 2016).

The full scan XPS spectrum demonstrated that there were no elements other than Bi, O, I and C in the pure BiOI powder (Fig. 3a). The weak signal of C 1s was derived from the adventitious hydrocarbon in the XPS instrument itself, reflecting that impurities could be considered negligible in the samples. In the XPS spectra of pure BiOI and BiOI-7, which was the powder scraped from GFC-7, the two peaks of Bi 4f at 164.0 and 159.0 eV (Fig. 3b) were assigned to Bi 4f5/2 and Bi 4f7/2 of Bi(III), respectively (Chang et al., 2013; Gao et al., 2017; Hu et al., 2018) and the peaks with binding energies of I 3d3/2 and I 3d5/2 were at 630.8 and 619.1 eV, respectively (Fig. 3c), confirming the existence of I− (Gao et al., 2017). The two peaks of O1s at 530.2 and 531.7 eV corresponding to the lattice oxygen of Bi-O and hydroxyl groups or O2 adsorbed on the surface of the catalysts, respectively (Fig. 3d) (Wang et al., 2011).

The silica sol method introduced Si on the surface of the BiOI powder. Besides the signals attributed by BiOI, a weak signal was detected in the region of Si 2p in BiOI-7 with a binding energy (BE) of 103.4 eV, which corresponded to that of silica sol (Fig. 3a), suggesting the existence of Si–O–Si in BiOI-7 (Yuan et al., 2016). For BiOI-7, the third peak of O1s appearing at 533.3 eV could also be ascribed to Si–O–Si bonds (Gao et al., 2017), which was confirmed by the Si–O signal of silica sol (Fig. 3a). In addition, the EDX spectra of BiOI-7 (Appendix A Fig. S1) also indicated that there was Si in BiOI-7.

Fig. 3b illustrates that the BEs of Bi in BiOI-7 shifted to lower binding energies by ca. 0.4–0.7 eV compared to the

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Fig. 2 – X-ray diffraction (XRD) patterns of BiOI, BiOI-7 and GFC-7.

Fig. 3 – X-ray photoelectron spectroscopy (XPS) results of BiOI and BiOI-7.
pure BiOI, implying that a chemical interaction might be formed between the Bi atoms and SiO₂. The smaller electronegativity of Si (1.8) than Bi (2.0) might lead to an increase of electron density around Bi atoms. Thus, the negative charge on Bi increased, resulting in a decrease in the BEs of Bi (Yuan et al., 2016). In the FT-IR spectra of both pure BiOI and BiOI-7 (Appendix A Fig. S2), the absorption peak at 3440 cm⁻¹ was ascribed to the stretching vibration absorption of O–H (Chang et al., 2013). The absorption peaks at 881 and 772 cm⁻¹ corresponded to the stretching vibrations of Bi–O bonds (Chang et al., 2013). There was an additional peak near 957 cm⁻¹ in BiOI-7, which was not observed in BiOI. This peak might be attributed to Si–OH groups, further supporting the existence of silica in the thin films (Davis and Liu, 1997; Neumann and Levin-Elad, 1997; Rasalingam et al., 2013).

Agreeing with a previous study (Chang et al., 2013), both pure BiOI and BiOI-7 presented as 3D hierarchical microspheres assembled from nanosheets (Appendix A Fig. S3). The surface morphology of the microspheres immobilized on the GFC was not apparently affected by the presence of silica. The silica present in the sol–gel served as an adhesion agent which glued the BiOI microspheres to the fiber surface or the interstices (Fig. 4a). With the increase in the iterations of the painting/drying process, more and more BiOI catalyst grew on the previously formed layers, forming a dense and bulky film of catalyst on the GFC (Fig. 4b–d). The BiOI catalysts gradually filled the interstices of the glass fiber cloth and the surface became smoother. The loading amounts of BiOI on the GFC were estimated by the weight difference of the GFC after and before loading BiOI, which were 5.6, 21.5 and 42.2 g/m², respectively, on GFC-3, -5 and -7. Efforts were made to further

Fig. 4 – Field emission scanning electron microscope (FESEM) images of GFC-1 (a), -3 (b), -5 (c) and -7 (d) films.
increase the thickness of the BiOI thin film. However, if the number of coatings was >7, an obvious flaking of BiOI powder from the GFC was observed.

High resolution transmission electron microscope (HRTEM) (Appendix A Fig. S4) was performed to further illustrate the crystal structure of the as-prepared catalysts. The HRTEM image of BiOI-7 scraped from GFC-7 shows the lattice spacing of 0.3 and 0.289 nm, corresponding to that of (102) and (110) diffraction peaks of BiOI, respectively. This coincides with the XRD result, supporting the supposition that the as-prepared catalysts were BiOI, and that mixing with SiO2 sol did not change its crystal structure.

The UV–vis diffuse reflectance spectra (DRS) were obtained to investigate the light absorption of the as-prepared catalysts, and the results are depicted in Appendix A Fig. S5a. Their absorption edges were at around 650 nm, while the intensity of BiOI-7 was slightly greater than that of BiOI in the visible region. As shown in Appendix A Fig. S5b, the band gaps of BiOI and BiOI-7 were estimated to be 1.76 and 1.57 eV, respectively. This reveals that the light absorption ability of BiOI-7 in the visible region was slightly higher than that of pure BiOI, which might be because the small amount of silica present enhanced the transmittance in the visible region (Shen et al., 2015).

2.2. Photocatalytic properties of the BiOI thin films

The photocatalytic activity of the BiOI thin films was evaluated by BPA degradation using the scraped BiOI-7 power from GFC-7 in quartz tubes. Fig. 5a shows that BPA was very stable under solar light irradiation without any photocatalyst. Compared to the pure BiOI, the BiOI-7 sample displayed lower degradation efficiency. The photoluminescence spectra and transient photocurrent results (Appendix A Fig. S6) indicated that the presence of SiO2 depressed the transfer of photogenerated electrons, which might explain the relatively lower degradation efficiency of BiOI-7 than pure BiOI. A similar result was reported for the BiOBr@SiO2 catalyst (Wang et al., 2018).

Another reason explaining the lower adsorption and weaker photocatalytic ability of BiOI-7 than BiOI was that BiOI-7 had smaller pores than BiOI (Wang et al., 2018). The N2 adsorption–desorption isotherms and pore size distributions of BiOI and BiOI-7 are illustrated in Appendix A Fig. S7. The BET surface area of BiOI-7 (24.8 m²/g) was higher than that of pure BiOI (16.9 m²/g). However, the average pore size of BiOI-7 (10.5 nm) was much smaller than that of pure BiOI (31.8 nm), which could be due to blocking of the pores by SiO2 sol.

Although BiOI-7 had relatively lower degradation efficiency than BiOI, it was still able to achieve satisfactory
performance in the degradation of BPA (Fig. 5b). For the BiOI thin films, the photocatalytic activity increased with increasing numbers of catalyst layers, which could be ascribed to more available BiOI photocatalyst being present on the GFC. In all cases, the removal rate of BPA by the thin films was greater than 90% in 2 hr, and BPA was almost completely degraded by GFC-7.

The effect of pH on the photocatalytic performance of GFC-7 was investigated (Fig. 5c). BPA could be well degraded with a degradation rate of 99.8% in 2 hr at pH 5–9. Reusability experiments were conducted to investigate the films’ lifetime. Fig. 5d illustrates that there was no significant decrease of photocatalytic efficiency after 5 cycles under the same reaction conditions, indicating that the as-prepared BiOI thin films were very stable for reuse.

2.3. Degradation performance of the TFFBR applied with GFC-7

Fig. 6 shows the photocatalytic degradation of BPA in the TFFBR under different working conditions, including the mass flow-rate (Q) and the inclination angle of the sloping plate (β). The fluid film thickness (d), residence time over the thin-film (Rt) and the recyle index of the continuous flow (RI) are important hydrodynamic parameters affecting degradation rates in a continuous flow TFFBR (Bousselmi et al., 2004). The calculation of these parameters is provided in Appendix A.

The β of the plate was found to be a vital parameter to affect the degradation efficiency (Fig. 6a). At pH of 7.5 and Q of 150 mL/L, the degradation rate (98%) at the β of 15° was significantly higher than those at 5° (23%) and 30° (40%). At β of 30°, the fluid film became thinner, with the d value decreasing from 0.22 to 0.18 mm, which should be beneficial for degradation since a thinner fluid film favors the mass transfer of BPA (Appendix A Table S2). However, the Rt decreased by 20% at the β of 30° compared to the value at 15°. The shorter Rt meant that BPA in the solution did not have enough time to react with the produced reactive oxygen species (ROS), leading to lower degradation efficiency. The longer Rt (by 43%) at the β of 5° compared to that at 15° should favor the degradation. Thus, the reduced degradation efficiency could be attributed to the increase in d (from 0.22 to 0.32 mm) (Appendix A Table S2). In a thicker fluid, the mass transfer of BPA in the solid–liquid interface became more difficult, making BPA unable to efficiently contact the produced ROS, then reducing the degradation efficiency. Thus, the β of 15° was selected as the optimum inclination angle for subsequent experiments.

Fig. 6b indicates the degradation rates at pH of 7.5, β of 15° and Qs of 150–250 mL/min. Under this condition, the Qs did not affect the degradation rate distinctly, which was in
the range of 95%–98% within 8 hr irradiation. This might be due to the integrated effects of the three hydrodynamic parameters: \(d\), \(R_t\) and \(R_I\). As the \(Q\) increased, \(d\) and \(R_I\) would increase while \(R_t\) decreased (Bousselmi et al., 2004), as shown in Appendix A Table S2. Greater \(R_I\) should favor the reaction, whereas shorter \(R_t\) and greater \(d\) should be against it. Due to the combined results, the degradation efficiency within a fixed time did not change much. At both 150 and 250 mL/min, the degradation rate was ca. 98%. Considering that higher flow rate would consume more electric energy, 150 mL/min and \(\beta\) of 15° were chosen for the following experiments.

In agreement with the tests in quartz tubes using BiOI thin films, the degradation efficiency of the TFFBR reactor with GFC-7 was the highest at pH 7.5 (Fig. 6c). The reusability test for the TFFBR showed that after 12 runs, the removal rate of BPA only slightly decreased to 96%. After a 6-months storage, the film in the TFFBR still displayed satisfactory degradation efficiency (>95%).

To further assess the applicability of the TFFBR, artificial sewage containing BPA was prepared and the degradation of BPA was tested. About 83% of BPA in the artificial sewage was degraded at pH of 7.5 within 8 hr (Fig. 6d), which was lower than the value in pure water. This may be due to the presence of inorganic ions, which were adsorbed on the thin films and depressed the photocatalytic degradation (Sudrajat and Babel, 2016). Some anions such as \(\text{NO}_3^-\) which has strong light absorption at a wavelength of <300 nm, may compete with the catalyst for the irradiation, thus reducing the photocatalytic degradation as well (Zhang et al., 2005). Previous studies reported that cations such as \(\text{Cu}^{2+}\) and \(\text{Ni}^{2+}\) inhibited the photocatalytic rate by trapping the electron-hole pairs (Hu et al., 2003). Further study is warranted to understand the impacts of the components in artificial sewage on the degradation efficiency.

### 3. Conclusions

A novel photocatalytic thin film, consisting of highly active BiOI nanoparticles immobilized on GFC using silica sol, was conveniently prepared and applied on a TFFBR for degradation of BPA. The photocatalytic degradation efficiency of the films increased with the number of coatings, and the sample with seven layers exhibited the highest photocatalytic performance. The as-prepared BiOI thin films were very durable and maintained high performance in a wide range of pH (pH 5–9) after running for many degradation cycles and after long-term storage. The GFC-7 applied on the TFFBR could degrade 98% of 2 L of BPA at 20 mg/L within 8 hr irradiation. The degradation efficiency was distinctly affected by the slope of the plate in the TFFBR. Although the degradation rate was relatively lower for artificial sewage, an 83% removal rate could be achieved in 8 hr irradiation. At the end of reaction, no separation process is necessary to remove the photocatalyst from the solution. Thus, the TFFBR based on glass fiber-supported BiOI films shows good prospects for practical wastewaster treatment.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jes.2019.01.004.

### REFERENCES


Yuan, L., Han, C., Pagliaro, M., Xu, Y., 2016. Origin of enhancing the photocatalytic performance of TiO$_2$ for artificial


