Insights into the photocatalytic degradation of triclosan over amorphous Nb$_2$O$_5$ catalysts

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Abstract

Photocatalytic degradation of triclosan is one of the most promising ways to eliminate triclosan pollution in water, yet it presents profound challenges to develop efficient photocatalysts to meet the demand of application. Herein, we demonstrate a facile hydrothermal-precipitation method to prepare amorphous Nb$_2$O$_5$ catalysts by using niobium(V) oxalate hydrate and ammonium carbonate. A series of amorphous Nb$_2$O$_5$ catalysts were obtained and analyzed by detail characterizations (XRD, XPS, BET and SEM). By optimizing synthesis conditions, it was found that 180/12-Nb$_2$O$_5$-(1:5) catalyst exhibited the optimal photocatalytic activity for triclosan degradation. Furthermore, the pseudo-first-order kinetic equations for triclosan degradation over 180/12-Nb$_2$O$_5$-(1:5) catalyst were investigated under conditions with different pH value. Among them, the triclosan degradation rate over 180/12-Nb$_2$O$_5$-(1:5) catalyst gave the highest reaction constant k (0.5 min$^{-1}$) and shortest half-period ($t_{1/2} = 0.17$ min$^{-1}$) at pH of 8. The presence of ionic state triclosan in base condition should be responsible for the improved degradation rate from acid to base reaction condition. Compared with molecular triclosan, ionic state triclosan exhibits very high reaction rate with radicals due to its strong electrophilic property. The high photocatalytic activity of 180/12-Nb$_2$O$_5$-(1:5) catalyst should be related to the presence of amorphous structure compared with calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst with highly crystalline structure. The existence of N species doping and nano-sheet structure in catalyst is also thought to promote the catalytic reaction.

1. Introduction

Nowadays, the water contamination caused by persistent organic pollutants has drawn more and more attentions worldwide because of their severe harm to both human health and environment [1–5]. Pharmaceuticals, dyes and other chemicals are some of the most recalcitrant organic pollutants, such as triclosan, a kind of extensively used antibiotic [2, 6, 7]. There are many methods developed for the organic pollutants elimination in water, such as adsorption on active carbon, membrane separation and so on [8]. However, these methods are suffering from serious problems of high operating costs and incomplete elimination of organic pollutants. Photocatalytic degradation of organic pollutants is considered as one of the most effective methods to eliminate organic pollutants owing to its advantages of high efficiency, low cost and free of secondary pollution. Thus, much efforts have been done to develop effective catalysts for photocatalytic degradation organic pollutants in water.

Various inorganic and organic materials based catalysts are effective for photocatalytic organic pollutants degradation [9–11]. The inorganic catalysts for photocatalytic degradation of pollutants in water includes TiO$_2$, Nb$_2$O$_5$, BiVO$_4$, CeO$_2$, ZnO and the relevant modified materials [12–20]. Then, the representative organic materials based catalysts for photocatalytic degradation are g-C$_3$N$_4$, MOFs and COFs [21–25]. Recently, many kinds of novel organic catalysts have attracted wide attention due to their easily tunable light capture range.
However, the application of organic catalysts are significantly limited because of their poor photocatalytic stability. Therefore, it seems that developing robust inorganic catalysts for photocatalytic degradation of pollutants in water is crucial. For instance, ZnO semiconductor with wide bandgap is a potential inorganic photocatalyst due to its direct bandgap [20]. Yet, the inorganic catalysts with wide bandgap are still in an urgent need. Thus, much works have been done in the modification of inorganic catalysts. For instance, Ribeiro et al found heterostructure such as g-C3N4/Nb2O5 could significantly improve the photocatalytic activity for drug amiloride and rhodamine B degradation, which was attributed to the effective migration of photogenerated electrons and holes in heterostructures [26]. Heshmatpour et al designed TiO2/Nb2O5/PANI and TiO2/Nb2O5/RGO as new nanocomposites for efficient degradation of organic pollutants [27]. The TiO2/Nb2O5/RGO exhibits significantly higher photocatalytic activity in degradation of organic dyes under visible light rather than that of TiO2/Nb2O5/PANI, TiO2/Nb2O5 and pure TiO2. Otherwise, morphology control has also been adopted to enhance the photocatalytic performance. Zhang et al illustrated the facile synthesis of urchin-like hierarchical Nb2O5 nanoshperes, which showed obviously increased visible light photocatalytic activity for Rhodamine B degradation [28]. The unique morphology of Nb2O5 nanoshperes and high adsorption rate for reactant resulted in the increase of photocatalytic activity. Moreover, the element doping in inorganic catalyst is one of the most effective strategy to improve its performance. For example, Juang et al reported the Pd-doped TiO2 photocatalyst for efficient degradation of methylene blue and methyl orange. It was found that a suitable amount of Pd dopant enhanced photocatalytic activity of TiO2 because of the decrease of bandgap and the increase of separation of generated electron-hole pairs [29]. Mohamed et al demonstrated the enhanced sunlight photocatalytic performance over Nb2O5/ZnO nanorod composites for phenol degradation under natural sunlight irradiation [30]. The improvement of photocatalytic activity over Nb2O5/ZnO nanorod was ascribed to the enhanced sunlight absorbing capability because of a good interface between two semiconductors with appropriate band structures alignment, thus, the transfer process of photogenerated charge could be proceeded efficiently. Hu et al prepared nitrogen-doped Nb2O5 nanobelt quasi-arrays for visible light photocatalytic contaminant degradation. The N-doped Nb2O5-400 showed much higher activity of photodegradation of MB in water compared to pristine Nb2O5 nanobelt [31]. Although much great progress has been achieved, there is still a big challenge to apply the available inorganic catalysts such as Nb2O5 into photocatalytic degradation of organic contaminant in actual water system due to the low activity of catalyst. Thus, it is still necessary to focus on the investigation of photocatalyst such as Nb2O5.

Herein, we demonstrate the facile method to synthesize the amorphous Nb2O5 catalysts doped by nitrogen species for triclosan degradation. A series of amorphous Nb2O5 catalysts were analyzed by detail characterization. And the 180/12-Nb2O5-(1:5) catalyst exhibited the optimal photocatalytic activity for triclosan degradation.

2. Experimental section

2.1. Chemicals and reagents

Niobium(V) oxalate hydrate and triclosan (TCS) were purchased from from Aladdin Co. China. Glacial acetic acid was bought from Shanghai Lianshi Chemical Reagent Co., Ltd. Other reagents such as NH3·H2O, Na2SO3, NaOH, HCl, ethanol and ammonium carbonate were obtained from Sinopharm Chemical Reagent Co. Ltd, China.

2.2. Preparation of catalysts

Typically, a series of Nb2O5 catalysts were synthesized by hydrothermal method [32]. Niobium(V) oxalate hydrate (C6H5H2NbO20·xH2O) of 0.8071 g was dissolved by the mixture solution of glacial acetic acid (10 ml) and deionized water (10 ml). Afterwards, a desired amount of ammonium carbonate ((NH4)2CO3) was added to the above solution according to the molar ratio of niobium (V) oxalate hydrate to ammonium carbonate (3:5, 2:5, 1:5, 1:6, 1:7).

Subsequently, the mixture solution was transferred to stainless steel autoclave and kept at desired time (t = 8 h, 12 h, 16 h, 20 h, 24 h) and temperature (T = 140 °C, 160 °C, 180 °C, 200 °C, 220 °C). The solid product was obtained by washing with water and ethanol solution, and then dried at 60 °C under vacuum for 8 h. The prepared catalysts were designated as T=t- Nb2O5-(xy) (T = temperature, t = time, xy = niobium(V) oxalate hydrate: ammonium carbonate).

2.3. Characterization of catalysts

Phase analyses of the obtained catalysts were conducted by x-ray diffraction (XRD, Brucker, D8 Advance type) using Cu Kα radiation, working at 40 kV and 40 mA. The XRD patterns were collected in the 2θ range of 10°–90°.
with a step of 0.02° at a scan rate of 0.1 s step⁻¹, and then analyzed by MDI Jade 6.0 software to perform refinement.

The x-ray photoelectron spectroscopy (XPS) of catalysts were analyzed by a Thermo Fischer ESCALAB 250Xi instrument with an Al Kα (15 kV, 10.8 mA, hv = 1486.6 eV) as the excitation light source under ca. 2 × 10⁻⁷ Pa ultrahigh vacuum, calibrated internally by the carbon deposit C (1s) (Eb = 284.6 eV).

FT-IR spectra in the range of 400–4000 cm⁻¹ were performed on a Thermal-Fischer Nicolet iS50 FTIR spectrometer equipped with an MCT detector.

Scanning electron microscopy (SEM) was undertaken using a ZEISS Gemini SEM 300 scanning electron-microscope, operated at an acceleration voltage of 10 kV.

Nitrogen sorption isotherms were collected on a Micromeritics ASAP 2020 system volumetric adsorption analyzer at 77 K in order to obtain the BET surface area of catalysts, which were calculated from the adsorption data at a relative pressure P/P₀ in the range of 0.04–0.20.

2.4. Photocatalytic performance evaluation for triclosan decomposition

The triclosan decomposition reaction was carried out in a closed quartz beaker (100 ml) with a 8 W UV Mercury lamp (λ = 254 nm, Shanghai Jiguang Special Lighting Company) as shown in scheme 1. Triclosan solution (5 mg l⁻¹, with a appropriate amount of 0.01 M NaOH solution to aid the dissolution) of 90 ml was added to the quartz beaker under stirring, then 10 ml of phosphate buffer solution was added to above solution. The lamp was turned on after the Nb₂O₅ catalyst being added. The decomposition reaction was terminated by adding a certain amount of Na₂SO₃ (5 g l⁻¹) solution at desired time, and the residual concentration of triclosan was determined by high performance liquid chromatography on an Agilent 1260 HPLC instrument equipped with a XDB-C18 column (4.6 mm × 250 mm, 5 μm). The detection wavelength was 230 nm, and the mobile phase was water and methanol (5/95) with a flow rate of 1.0 ml min⁻¹.
3. Result and discussion

Figure 1 shows the XRD patterns of Nb$_2$O$_5$ catalysts prepared at temperature of 180 °C for 12 h, which is under condition of different molar ratio of niobium (V) oxalate hydrate to ammonium carbonate. All the catalysts in the figure 1 give the characteristic peak at 27.5°, which should be attributed to the presence of Nb$_2$O$_5$ (PDF No. 70-2679). This result indicates the successful synthesis of Nb$_2$O$_5$ but with mainly amorphous phase. According to the XRD result, it seems that the molar ratio of niobium (V) oxalate hydrate to ammonium carbonate has no influence on the crystallinity of Nb$_2$O$_5$ phase.

The photocatalytic degradation performance tests of triclosan under visible light irradiation (λ = 254 nm) over Nb$_2$O$_5$ prepared at different molar ratio of C$_{10}$H$_5$NbO$_{20} \cdot x$H$_2$O to (NH$_4$)$_2$CO$_3$ were evaluated as shown in figure 2. All Nb$_2$O$_5$ catalysts can remove triclosan efficiently and the complete elimination can be achieved at ca. 15 min (figure 2(a)). Moreover, it can be clearly observed that the photocatalytic degradation rate of obtained Nb$_2$O$_5$ catalysts presented in ‘volcano type’ trend when the molar ratio of C$_{10}$H$_5$NbO$_{20} \cdot x$H$_2$O to (NH$_4$)$_2$CO$_3$ increases.

Figure 2. The effect of the molar ratio of C$_{10}$H$_5$NbO$_{20} \cdot x$H$_2$O to (NH$_4$)$_2$CO$_3$ on the photocatalytic degradation of triclosan under visible light irradiation (λ = 254 nm) over Nb$_2$O$_5$: (a) the removal rate versus time; (b) the removal rate at time of two minutes.

Figure 3. The XRD patterns of Nb$_2$O$_5$ catalysts prepared with different times (3a) and temperature (3c); the photocatalytic degradation of triclosan over Nb$_2$O$_5$ catalysts (3b) and (3d).

Figure 3. The effect of the molar ratio of C$_{10}$H$_5$NbO$_{20} \cdot x$H$_2$O to (NH$_4$)$_2$CO$_3$ on the photocatalytic degradation of triclosan under visible light irradiation (λ = 254 nm) over Nb$_2$O$_5$; (a) the removal rate versus time; (b) the removal rate at time of two minutes.
was gradually increased from 1:7 to 3:5 figure 2(b). Among all the catalysts, 180/12-Nb2O5-(1:5) possessed the highest photocatalytic activity for triclosan degradation.

The effects of synthesis time and temperature have also been investigated. Figure 3 gives the XRD patterns of Nb2O5 catalysts synthesized under desired conditions. And the relevant photocatalytic performances for triclosan degradation are also evaluated (figures 3(b) and (d)). According to the related XRD results in figures 3(a) and (c), the conditions of synthesis time and temperature have also no effects on the phase composition of Nb2O5 species, which mainly contains amorphous Nb2O5. However, both the synthesis temperature and time showed obvious effect on the photocatalytic performances for degradation of triclosan. According to above results, the preparation condition related to 180/12-Nb2O5-(1:5) catalyst should be optimal.

Diffuse reflectance ultraviolet-visible spectroscopy (UV–Vis) spectra were carried out to explore band gaps of the prepared amorphous Nb2O5 catalysts(Figure 4 a). According to the UV–Vis spectra, the prepared amorphous Nb2O5 are UV light responsive catalysts. The difference of optical band gap between amorphous
Nb_2O_5 catalysts could be ignored (Figure 4 b–4 d), although the difference in photocatalytic performance are obvious for these catalysts.

Figure 5 shows the photocatalytic performance of triclosan degradation over 180/12-Nb_2O_5-(1:5) catalyst under different light irradiation condition. Compared with results of degradation performance under dark and natural light condition, it can be inferred that the 180/12-Nb_2O_5-(1:5) catalyst is light responsive and the photocatalytic performance is obviously improved under natural light irradiation. Moreover, the degradation performance of triclosan is significantly increased under UV light irradiation, the degradation ratio is up to 99.9% at 10 min. Although the triclosan can be also degraded under only UV light irradiation, the degradation rate and complete elimination ratio is much lower than that over 180/12-Nb_2O_5-(1:5) catalyst with same time.

Considering the remarkable effect of light irradiation condition on the triclosan degradation performance, the influence of UV light intensity was also investigated as shown in figure 6. It can be seen that the degradation performance for triclosan is increased as the light intensity increases from 1500 \( \mu W \text{ cm}^{-2} \) to 6000 \( \mu W \text{ cm}^{-2} \) over 180/12-Nb_2O_5-(1:5), which implies that the increase of light intensity is favorable for enhancing photocatalytic activity for triclosan degradation.

Besides, the influence of triclosan concentration on the degradation rate has also been investigated because the concentration of triclosan in the waste water can vary (figure 7). It can be found that the triclosan concentration has only a moderate effect on the degradation reaction rate and complete elimination ratio, and
the elimination ratio is near 99.9% at 10 min for three kinds of triclosan concentrations. Thus, it is reasonable to infer that 180/12-Nb2O5-(1:5) catalyst can be potentially used for degrading triclosan with various concentration in the actual polluted water.

As for the degradation of triclosan in aqueous solution, the effect of pH on the photocatalytic triclosan degradation also should be considered. Figure 8 (a) gives the triclosan degradation over 180/12-Nb2O5-(1:5) catalyst with different pH value, it can be found that the pH value shows significant effect on the photocatalytic degradation of triclosan. The order of triclosan degradation rate at five minutes is given in the figure 8 (b), which indicates that the highest activity for triclosan degradation reaction over 180/12-Nb2O5-(1:5) catalyst is obtained with pH value of 8.

Furthermore, the pseudo-first-order kinetic equations for triclosan degradation over 180/12-Nb2O5-(1:5) catalyst were also investigated under different pH condition as shown in table 1. Among them, the triclosan degradation rate over 180/12-Nb2O5-(1:5) catalyst gave the highest reaction constant k (0.5 min⁻¹) and shortest half-period (t₁/₂ = 0.78 min⁻¹) at pH of 8. The increase of degradation rate from acid to base reaction condition should be ascribed to the formation of ionic state triclosan in base condition (pKa of triclosan is 8.1). Compared with molecular triclosan, the ionic state triclosan possessing strong electrophilic property shows very high reaction rate with radicals [33, 34].

Figure 9 (a) gives the performance of photocatalytic triclosan degradation over pristine and calcined 180/12-Nb2O5-(1:5) catalyst. The photocatalytic activity and complete triclosan degradation ratio of pristine 180/12-Nb2O5-(1:5) catalyst is obviously higher than that of 180/12-Nb2O5-(1:5) (calcined 500 °C) catalyst.

| pH | Fitted equation | k (min⁻¹) | R² | t₁/₂ (min) |
|----|----------------|-----------|----|-----------|
| 5  | ln(c/c₀) = -0.06 t - 0.02 | 0.06 | 0.98 | 10.52     |
| 7  | ln(c/c₀) = -0.13 t - 0.19 | 0.13 | 0.99 | 4.00      |
| 8  | ln(c/c₀) = -0.50 t - 0.61 | 0.50 | 0.98 | 0.17      |
| 9  | ln(c/c₀) = -0.27 t - 0.17 | 0.27 | 0.99 | 1.97      |

Figure 8. (a) Photocatalytic degradation of triclosan solution with various pH values over 180/12-Nb2O5-(1:5) (UV light irradiation: 3000 µW cm⁻²; triclosan concentration: 5 mg l⁻¹); (b) the removal rate at five minutes.

Figure 9. (a) Photocatalytic degradation of triclosan solution over pristine and calcined 180/12-Nb2O5-(1:5) catalyst (UV light irradiation: 3000 µW cm⁻²; triclosan concentration: 5 mg l⁻¹); (b) XRD patterns of pristine and calcined 180/12-Nb2O5-(1:5) catalyst.
Based on the XRD result in figure 9(b), the crystallinity of 180/12-Nb$_2$O$_5$-(1:5) (calcined 500°C) catalyst remarkably improved, while the photocatalytic activity decreased. The above result indicated that the prepared Nb$_2$O$_5$ amorphous structure played very important roles on the photocatalytic performance for triclosan degradation.

In order to clearly understand the decrease of photocatalytic performance over calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst for triclosan degradation, a detail characterizations were performed. Firstly, the special surface area tests of pristine and calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst were analyzed by N$_2$ adsorption-desorption experiment. The BET surface area of pristine and calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst were 36.7 m$^2$ g$^{-1}$ and 54.0 m$^2$ g$^{-1}$, respectively. The increase of surface area excludes the possibility of pore clogging after calcination. Afterwards, the FT-IR and XPS spectra were also conducted as shown in figure 10. The appearance of characteristic vibration peak of C-N at 1406 cm$^{-1}$ implies the presence of carbon-nitrogen species in 180/12-Nb$_2$O$_5$-(1:5) catalyst, however, that characteristic vibration peak disappeared after the calcination process. This result can be ascribed to that the carbon-nitrogen species are unstable and decompose at high temperature (500°C). Based on XPS spectra of 180/12-Nb$_2$O$_5$-(1:5) catalyst, the binding energies of N1s appearing at 406.1 and 394.9 eV are attributed to graphitic-N and pyridinic-N species, respectively. And the signal of graphitic-N species disappeared in calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst, which was consistent with the result of FT-IR. The generation of graphitic-N and pyridinic-N species can be ascribed to the using of ammonium carbonate precursor. Figure 11 shows the SEM pictures of fresh and calcined 180/12-Nb$_2$O$_5$-(1:5) catalyst. The pristine 180/12-Nb$_2$O$_5$-(1:5) catalyst showed nano-sheet structure while the nano-sheet obviously aggregated to particles after calcination.

According to the above result, it is reasonable to infer that the appearance of graphitic-N species and the formation of nano-sheet structure could be responsible for the increase of photocatalytic activity for triclosan degradation over the prepared amorphous Nb$_2$O$_5$.

4. Conclusions

In summary, this work presented a facile hydrothermal-precipitation method to prepare amorphous Nb$_2$O$_5$ catalyst for photocatalytic triclosan degradation. Based on the optimization of synthesis conditions, the 180/12-Nb$_2$O$_5$-(1:5) catalyst showed the highest photocatalytic activity for triclosan degradation. The formation of ionic state triclosan in base condition resulted in the improved photocatalytic activity for triclosan.
degradation. The triclosan degradation rate over 180/12-Nb_2O_5-(1:5) catalyst gave the highest reaction constant k (0.5 min^{-1}) and shortest half-period (t_{1/2} = 0.17 min^{-1}) at pH of 8. In addition, the amorphous 180/12-Nb_2O_5-(1:5) catalyst exhibited higher activity than the crystallized 180/12-Nb_2O_5-(1:5)(calcined 500 °C) catalyst. The existences of graphitic-N species and nano-sheet structure in pristine 180/12-Nb_2O_5-(1:5) catalyst are beneficial for the improvement of photocatalytic activity.

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References

[1] Montaseri H and Forbes P A 2016 Trends Anal. Chem. 85 221–31
[2] Inderayas A et al 2020 Mater. Res. Express 7 025033
[3] Wang S and Wang J 2019 Chem. Eng. J. 356 350–8
[4] Awfa D, Ateia M, Fujii M, Johnson M and Yoshimura C 2018 Water Res. 142 26–45
[5] Tang Y, Shen F, Huang H, Shang H, Mao H, Ma J, Liao Y and Zhao S 2020 Mater. Res. Express 7 025040
[6] Li Q, Yu J, Chen W, Ma X, Li G, Chen G and Deng J 2018 Chemosphere 207 449–56
[7] Marzouqui F A, Selvaraj R and Kim Y 2019 Mater. Res. Express 6 125538
[8] Wang J, Wang Z, Veirera J, Wolfson J, Pingtian G and Huang S 2019 Ultrason. Sonochem. 55 273–8
[9] Prakash A, Singh S, Gupta J and Bahadur D 2019 Mater. Res. Express 6 125061
[10] Dziike F, Franklyn P, Durbach S, Maubanea M and Hlekelele L 2018 Mater. Res. Bull. 104 220–6
[11] Liang B and Zhang W 2019 Mater. Res. Express 6 115066
[12] Wang W, He Q, Xiao K and Zhu L 2018 Mater. Res. Express 10 035510
[13] Son S, Ko G and Zoh K 2009 J. Hazard. Mater. 166 954–60
[14] Lopes O, Paris E and Ribeiro C 2014 Appl. Catal. B Environ. 144 800–8
[15] Li M, Xu G, Guan Z, Wang Y, Yu H and Yu Y 2019 Sci. Total Environ. 664 230–9
[16] Yu T, Liu L and Yang F 2017 Chin. J. Catal. 38 270–7
[17] Zhao H, Zhang G and Zhang Q 2014 Ultrason. Sonochem. 21 991–6
[18] Gobbo S D, Poolwong J, D’Elia V and Ogawa M 2020 Cryst. Growth Des. 20 5508–25
[19] Wang H, Cai Y, Wang C, Xu H, Fang J and Yang Y 2020 CrystEngComm 22 4154–61
[20] Khanah S H and Pathak B 2020 Environ. Nanotechnology, Monit. Manag. 13 100290
[21] Zhou X, Xu D, Chen C and Hu Y 2020 Chem. Eng. J. 384 123324
[22] Liu Y et al 2020 Appl. Catal. B Environ. 266 118624
[23] Dluka S, Kumar R, Deep A, Kurade M, Ji S and Jeon B 2019 Coordin. Chem. Rev. 380 330–52
[24] Priy B, Li X, Liu T, Wu J, Li Y, Xiao J and Li Z 2018 Chem. Eng. J. 337 351–71
[25] Carvalho K, Nogueira A, Lopes O, Byznyski G and Ribeiro C 2017 Ceram. Int. 43 3521–30
[26] Silva G, Carvalho K, Lopes O and Ribeiro C 2017 Appl. Catal. B Environ. 216 70–9
[27] Zarrin S and Heshmatpour F 2018 J. Hazard. Mater. 351 147–59
[28] Chen J, Wang H, Huang G, Zhang Z Q, Han L, Song W, Li M and Zhang Y 2017 J. Alloys Compd. 728 19–28
[29] Nguyen C, Fu C and Huang R 2018 J. Clean Prod. 202 413–27
[30] Lam S, Sin J, Satoishi I, Abdullah A and Mohamed A 2014 Appl. Catal. A Gen. 471 126–35
[31] Hu B and Liu Y 2015 J. Alloys Compd. 635 1–4
[32] Li S, Wang Y, Zhu W, Lian H, Huang Y, Yu Y, Qiu J, Zhao Y, Yong Y and Li H 2019 J. Mater. Chem. A 7 693–703
[33] Kliegman S, Fustis S, Arnold W and McNeill K 2013 Environ. Sci. Technol. 47 6756–63
[34] Constantin L, Nitoi I, Griseta N and Constantin M 2018 J. Ind. Eng. Chem. 58 155–62