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Effect of dissolved oxygen on the efficiency of electro-Fenton process on Fe_2O_3/graphite perforated tubular electrode

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Abstract

Electrodes based on carbon materials modified with iron oxides or metallic iron have attracted much attention in the field of heterogeneous electro-Fenton process for the removal of various organic pollutants. In this study, perforated tubular graphite electrode modified with Fe_2O_3 (Fe_2O_3/GT) by electrochemical deposition was used as a cathode material. The obtained electrode was characterized by electron microscopy, energy-dispersive spectroscopy and Raman spectroscopy. The oxidation of rhodamine B in the electro-Fenton process by bubbling air through the perforated tubular graphite cathode at different air pressures was investigated. The complete decolorization of the rhodamine B solution was achieved in 20 min of electrolysis using Fe_2O_3/GT as a cathode at a current density of 29.85 mA/cm² and a pressure of 0.1 MPa. The use of higher pressure leads to complications in the equipment design of the electro-Fenton process. Carrying out the electro-Fenton process at a pressure of 0.6 MPa leads to a decrease in the energy consumption by 0.07 kW·h/mg. A possible mechanism for the oxidation of rhodamine B by bubbling air through the perforated tubular graphite cathode modified with Fe_2O_3 was proposed.

Accompanying information

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Electo-Fenton; rhodamine B; tubular graphite; dissolved oxygen

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1. Introduction

Advanced oxidation processes are currently widely used for the removal of various organic pollutants such as phenols [1,2], pesticides and insecticides [3,4], antibiotics and antiviral drugs [5–8], dyes [9–11], etc. Advanced oxidation processes are based on the generation of active oxygen species involved in the oxidation of organic pollutants. Among the active oxygen species, the hydroxyl radical (•OH) is the strongest oxidizer with a potential of 2.8 V [12, 13]. The most studied processes for •OH generation are the Fenton method and its modifications [14–16]. One of the modifications of the Fenton process is electro-Fenton, which uses the oxygen reduction reaction at the cathode to generate hydrogen peroxide and then the hydroxyl radical [17–20]. The Electro-Fenton process has attracted much attention from researchers at present, both in terms of improving the efficiency of the process and in terms of obtaining various highly efficient oxygen reduction electrodes with simultaneous generation of •OH radicals [21–23].

Electro-Fenton, along with anodic oxidation, is one of the widely used advanced oxidation processes for the removal of organic compounds [24-27]. The process is based on the electrochemical generation of the Fenton reagent. In the implementation of the electro-Fenton process, hydrogen peroxide is formed by the reduction of oxygen [28, 29]:

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2. \qquad (1)$$

Electrochemically generated H_2O_2 reacts with an externally added catalyst (Fe^{2+}) to form •OH homogeneously via the Fenton reaction:

$$H_2O_2 + Fe^{2+} \rightarrow Fe^{3+} + OH^- + \bullet OH. \quad (2)$$

Continuous formation of •OH is then ensured by electroregeneration of Fe^{2+} from the reduction of Fe^{3+} formed in the Fenton reaction

$$Fe^{3+} + e^- \rightarrow Fe^{2+}. \quad (3)$$

•OH further reacts with organic pollutants, resulting in their oxidation to biodegradable species, which can be further removed by biological post-treatment [30]. The most optimal pH value is around 3 for the electro-Fenton process to occur. At higher pH values, the catalytic Fe^{2+} ions may precipitate to form iron-containing sludge. Based on this, it was proposed to use reactions of heterogeneous generation of •OH radicals on the surface of solid iron-containing catalysts applied to the cathode surface as an alternative [31–34]. In particular, iron oxides α-Fe_2O_3, γ-Fe_2O_3, Fe_3O_4, etc. are widely used for this purpose on various carriers [35–38]. In this case, Fe_2O_3 acts as a heterogeneous catalyst for the decomposition of hydrogen peroxide to form •OH [39, 40].

In this aspect, in recent years, studies have been carried out to the selection of cathode materials for the electro-Fenton process [41–43]. Carbon based materials are widely used as cathode materials for the generation of hydrogen peroxide by oxygen reduction [44–48]. Electrodes based on carbon and graphite fibers [49–51], carbon felt [52, 53], carbon nano-tubes [13], carbon aerogel [54], etc. were studied as cathode materials in the electro-Fenton process [55, 56]. Modification of cathode materials with iron compounds or zero-valent iron allows the generation of hydroxyl radicals with simultaneous reduction of oxygen to hydrogen peroxide [57–60]. For example, the authors of the work [61] suggested using the carbon felt loaded with zero-valent iron and iron oxide as a cathode material in the electro-Fenton process for the removal of bisphenol A. Etched graphite felt was used as a matrix material for the deposition of Fe_2O_3 nanoparticles doped with Cu and then – as a cathode material in the electro-Fenton process for the removal of sulfamethoxazole [62]. A carbon felt cathode coated with iron oxides was prepared by electrodeposition of Fe^{3+}. The fabricated cathodes were used in the oxidation of malachite green dye at pH 3.0 using heterogeneous electro-Fenton and photo-electro-Fenton in a stirred reactor [63–66].

Although the fabricated electrodes have a large surface area, there is still the problem with low hydrogen peroxide yield. Hydrogen peroxide generation by oxygen reduction is a key reaction to increase the efficiency of the electro-Fenton process [67, 68]. Oxygen supply is one of the factors that increase the productivity of the electro-Fenton process. For example, oxygen bubbling in the electrochemical reactor leads to an increase the concentration of dissolved oxygen and the mass transfer rate, which ultimately leads to an increase in the efficiency of the process [55, 69]. To do this, different types of reactors were developed [70, 71], and the surface of cathode materials was modified [72]. In this regard, the attention of researchers is directed to the creation of different types of reactors with high oxygen reduction rates, and the most promising solution is to supply oxygen to the electrochemical reactor at different rates [73, 74].

In this study, a perforated tubular graphite cathode was developed through which oxygen was bubbled into the electrochemical reactor. To increase the rate of hydroxyl radical generation, the graphite electrode was modified with Fe_2O_3 by electrochemical deposition. Rhodamine B (RhB) was chosen as a model pollutant. The impact of various operating parameters such as air pressure on the removal efficiency of RhB was investigated.

2. Experimental

2.1. Fe_2O_3/GT electrode preparation

The graphite electrode was modified by electrochemical reduction of iron oxide (III) from a pyrophosphate solution. Graphite tubes, previously sealed hermetically on both sides to prevent iron deposition on the inner surface of the tube, were used to apply Fe_2O_3. Electrolysis was preliminarily carried out in a solution containing $FeSO_4$ with a concentration of 2.0 g/l, $K_4P_2O_7$ with a concentration of 10 g/l and NaOH – 1 g/l. The resulting electrode was annealed at a temperature of 450 °C. After this, the tubular graphite electrode was perforated.

2.2. Fe_2O_3/GT characterization

The morphology of the samples was characterized using an Aspex ExPress VP scanning electron microscope-microanalyzer (FEI, USA). The structures were characterized by Raman spectroscopy using an Ntegra Spectra research com-plex of probe-based confocal laser microscopy (ZAO NTI, Russia) with excitation by a laser of $\lambda = 532$ nm.

2.3. Electro-Fenton process efficiency

Graphite tubes (China) were used as electrode materials. The diameter of the graphite tube was 1 cm, the length was 25 cm. A thread was cut on the graphite cathode for connecting the nozzle for supplying air under pressure. The graphite tubes were placed in a polyethylene vessel with a wall thickness of 10 mm and a length of 15 cm, where four perforated graphite tubes were placed vertically. The distance between the electrodes was 0.5 cm. Compressed atmospheric air was passed through the perforated graphite tubes. The principle of electrolysis under pressure is described in detail in our work [75].

The efficiency of the electro-Fenton process was estimated by oxidation rhodamine B in 0.1 M Na_2SO_4 solution. Oxygen was bubbled into the electrochemical reactor using a compressor. The dye concentration was determined using a pre-built calibration curve. The optical density of RhB was measured using a scanning UV/Vis

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spectrophotometer of the SF-2000 series (Russia). After the measurement, the solution was poured back into the electrochemical reactor, and the process was continued.

The calculation of energy consumption was carried out using the following equation:

$$EC = \frac{U \cdot I \cdot t}{\Delta C}, \qquad (4)$$

where U – voltage, V; I – current, A; t – electrolysis time, h; ΔC – the concentration change, mg.

3. Results and Discussion

The morphology of the electrode was characterized by investigated various areas of the electrode surface. Figure 1 shows an image of the surface, EDX and Raman spectra of the selected area of the cathode surface.

As can be seen from Figure 1a, spherical particles with a size of about 1.85 μm are formed on the surface of the graphite electrode. These particles according to the EDX spectra correspond to iron (III) oxide. The EDX spectra shown in Figure 1b correspond to the area of the electrode surface marked in the SEM image. The iron content in this area is 7 wt.% (Figure 1b). The presence of oxygen and iron in this area indirectly confirms the formation of iron oxide on the electrode surface. White inclusions on the electrode surface apparently correspond to iron oxides. Thus, during the electrochemical reduction of iron from a pyrophosphate electrolyte with subsequent heating at 450 °C in atmospheric air, iron is deposited on the surface of the graphite electrode in the form of iron (III) oxide microparticles.

The Raman spectra were obtained for the determination of the phase modification of Fe_2O_3 on the graphite surface.

As can be seen from Figure 1d, two bands at 1347 cm^{-1} and 1589 cm^{-1} are attributed to the sp^3 and sp^2 states of carbon in graphite [76]. The peaks at 342.3 cm^{-1} and 738.9cm^{-1} are characteristic bands for maghemite (γ-Fe_2O_3) [77]. The mode at 1020 cm^{-1} is characteristic of hydrated phosphate bonds (P-OH bonds) [78] and shows the absorption of the pyrophosphate electrolyte by graphite.

The obtained electrode was used to study the process of electrochemical reduction of oxygen to hydrogen peroxide. The reduction of oxygen to hydrogen peroxide plays an important role in the electro-Fenton process [79]. In this case, iron (III) oxide deposited to the graphite surface is a catalyst for the decomposition of hydrogen peroxide formed due to the reduction of oxygen. In this case, highly active hydroxyl radicals are formed, participating in the oxidation of organic compounds.

The initial electrical resistance of the graphite tube was 4.6 Ohm; the deposition of Fe_2O_3 leads to an increase in resistance to 1500 kOhm when measuring the contact between Fe_2O_3 and the graphite substrate. However, such a high resistance does not affect the overall energy consumption of the electro-Fenton process using the resulting electrode, since Fe_2O_3 was not applied to the entire surface of the electrode. The internal part of the graphite tube remains uncoated, and Fe_2O_3 was deposited only on some areas of the graphite.

As shown in Figure 2 by the cathodic voltammetry curves on Fe_2O_3 modified graphite in 0.1 M Na_2SO_4 solution, oxygen reduction occurs at the potential range starting from 0.1 V. The primary electrochemical process is the reduction of oxygen at the electrode.

The operating characteristics of a graphite cathode were studied during oxidation of RhB in 0.1 M Na_2SO_4 solution at different air pressures at neutral pH. Figure 3a shows the kinetic curves of oxidation of the RhB using different cathode materials. As can be seen from the obtained data, the highest RhB oxidation rate is observed when using Fe_2O_3 modified graphite as the cathode material with simultaneous air supply through a graphite tube under a pressure of 0.1 MPa.

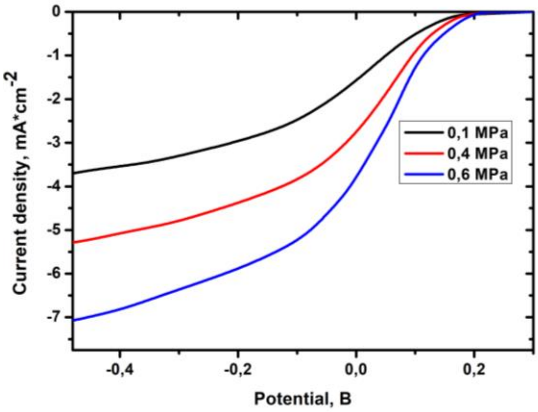

Figure 2 Oxygen reduction voltammetry curves on a graphite electrode in 0.1 M Na_2SO_4 solution at different air pressures (MPa).

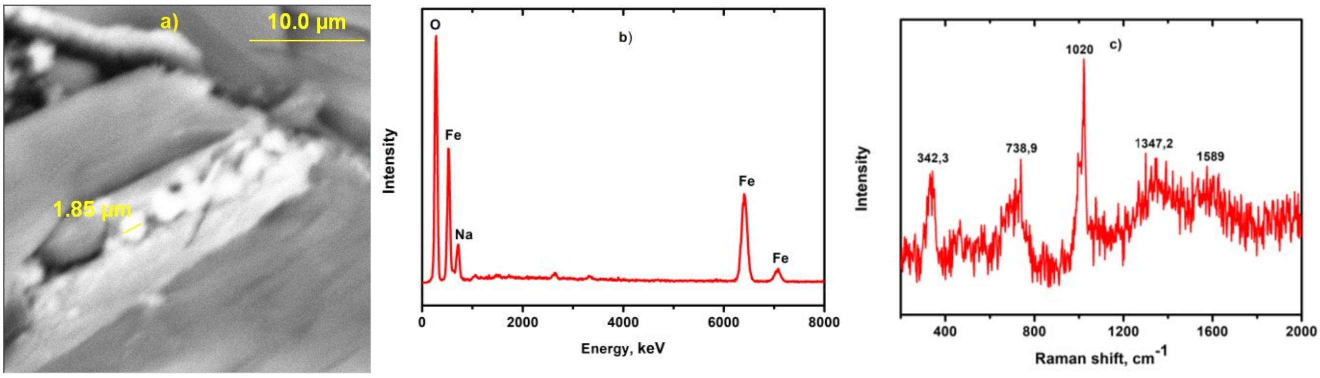

Figure 1 SEM image (a), EDX (b) and Raman spectra (c) of the selected area of the tubular graphite cathode surface, modified with Fe_2O_3.

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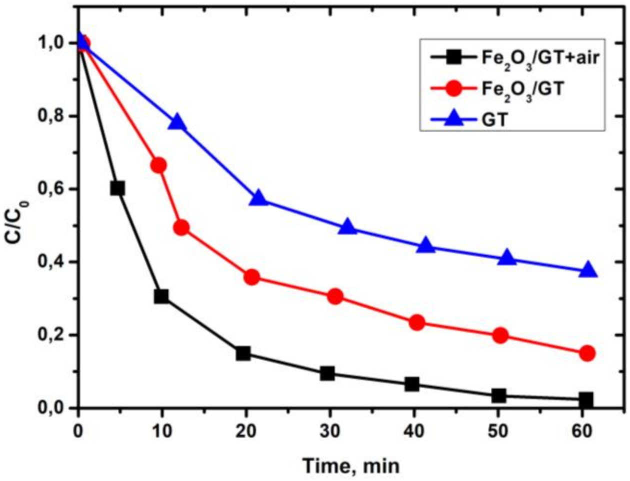

Figure 3 Kinetic curves of RhB oxidation during electrochemical generation of hydrogen peroxide using different cathode materials (C = 0.1 M Na_2SO_4, anode – graphite tube, P = 0.1 MPa with air supply; C = 100 mg/l).

Although the dye oxidation rate increases when using a Fe_2O_3 modified graphite electrode, the H_2O_2 accumulation rate is still low compared to the oxygen reduction rate. This is due to the low solubility of molecular oxygen in aqueous solutions under normal conditions (0.1 MPa pressure and ambient temperature). The solubility of oxygen under these conditions is approximately 40 mg·l^{-1} when pure oxygen is supplied and 8 mg·l^{-1} when air is used [80, 81]. In addition, it should be noted that, simultaneously with the formation of hydrogen peroxide, a parasitic reaction of hydrogen evolution proceeds at the cathode, and at the anode, in addition to dye oxidation, a reaction of oxygen evolution from water occurs.

Since air supply to the electrochemical reactor through a Fe_2O_3 modified tubular graphite cathode promotes the intensification of the oxidation process, we investigated the effect of the supplied air pressure on the oxidation rate of RhB due to the electro-Fenton process. The obtained experimental data in the form of kinetic curves of RhB oxidation at different pressures and the effect of pressure on the rate of the electro-Fenton process are shown in Figure 4a.

As shown in Figure 4b, the decolorization efficiency of RhB solution using Fe_2O_3/GT electrode and passing air under 0.1 MPa pressure reached 94% after only 10 minutes of treatment at a current density of 29.85 mA/cm². Increasing the current density leads to an increase in the rate of anodic oxidation of RhB on the graphite anode [19]. However, further increase in the current density leads to the destruction of the graphite anode.

An increase in the air pressure from 0.1 MPa to 0.6 MPa leads to an increase in the oxidation rate of the RhB by 1.6 times. Air supply at higher pressures through a tubular Fe_2O_3/GT cathode leads to an increase in the yield of hydrogen peroxide due to increasing solubility of oxygen, which promotes the rate of the electro-Fenton process (Figure 4c). The use of high pressures leads to increased requirements for the reactor design for the electro-Fenton process. Based on this, the low air pressures (0.1–0.6 MPa) were used in this investigation.

The comparative data of the rate constant, decolorization of RhB and energy consumption using different cathode materials are presented in Table 1.

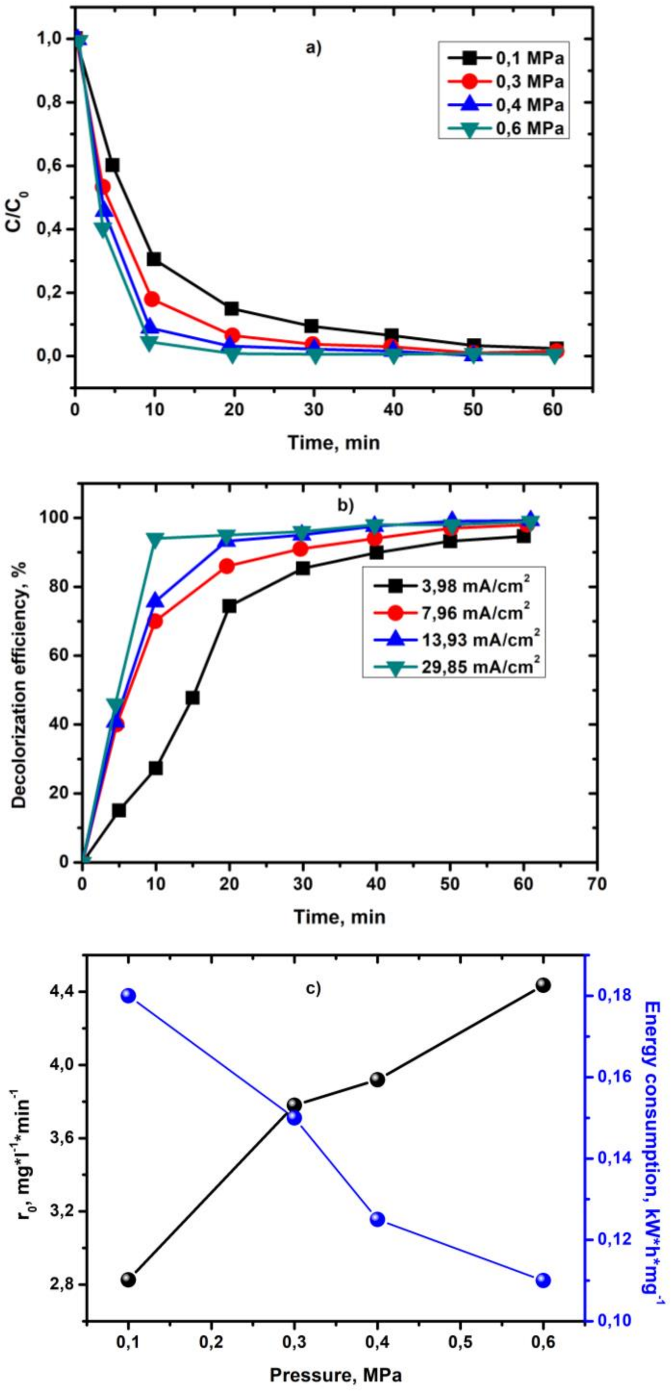

Figure 4 Kinetic curves of RhB oxidation by electro-Fenton process at different air pressures (i = 7.96 mA/cm²) (a); decolorization of Rhodamine B solution at different current densities (b) (P = 0.1 MPa) and the effect of oxygen pressure on the electro-Fenton process rate and energy consumption (c) (C = 0.1 M Na_2SO_4, anode – graphite tube, cathode – Fe_2O_3/GT; C = 100 mg/l, i = 29.85 mA/cm², P = 0.6 MPa).

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Table 1 Effect of cathode material on the rate constant, decolorization and energy consumption of the electro-Fenton process.

Electrode	Rate constant, min^{-1}	Decolorizations, %	Energy consumption, $kW\cdot h\cdot mg^{-1}$
GT	0.016	62.6	0.15
Fe_2O_3/GT	0.031	85.1	0.19
Fe_2O_3/GT+air	0.056	99.6	0.11

As can be seen from Table 1, the rate constant of the process and the degree of bleaching of the RhB dye solution increase in the range of cathode materials used GT Fe_2O_3/GT Fe_2O_3/GT+air. This is due to the decomposition of hydrogen peroxide generated on the cathode to hydroxyl radicals due to the heterogeneous Fenton process on the Fe_2O_3 surface [82, 83]. In this case, the supply of air under pressure leads to an increase in the yield of hydrogen peroxide and a corresponding increase in the efficiency of the RhB oxidation process. The power consumption does not change significantly when using any of the cathode materials under consideration. A slight increase when using Fe_2O_3/GT is due to an increase in resistance at the boundary between graphite and the applied Fe_2O_3. And the decrease in energy consumption with increasing pressure is associated with a decrease in the size of gas bubbles and a corresponding decrease in the resistance of the electrolyte [81].

The oxygen bulbed through the tubular cathode is reduced to hydrogen peroxide, with subsequent formation of hydroxyl radicals on the electrode surface due to the heterogeneous Fenton-like process involving Fe_2O_3 [39, 40]. Hydroxyl radicals subsequently participate in the oxidation of dye molecules, ultimately forming carbon dioxide and water (Figure 5).

Carrying out the electro-Fenton process under a pressure of 0.6 MPa also allows decreasing the energy costs and energy consumption is reduced by 0.07 $kW\cdot h\cdot mg^{-1}$. Ultimately, this can lead to decrease the cost of the electrochemical treatment of wastewater containing various organic compounds.

4. Limitations

On a graphite electrode, oxygen reduction occurs at a low rate. The use of high air pressures in the electro-Fenton process partially solves this problem, but at the same time, the hardware design of the process is complicated, associated with the use of high pressures. In addition, there is a problem of the determining the proportion of oxidized dye on the anode and due to the electro-Fenton process. In the future, we will investigate the electro-Fenton process with use a Fe_2O_3 modified hydrophobized graphite electrode with air bubbled at atmospheric pressure. For the determination of the anodic and cathodic processes contribution in the oxidation of RhB, we will study the electro-Fenton process in an electrochemical reactor with separated chambers.

5. Conclusions

In this study Fe_2O_3 particles were deposited on the surface of a perforated tubular graphite electrode by electrochemical deposition from a pyrophosphate electrolyte. The resulting Fe_2O_3/GT electrode was used as a cathode in the electro-Fenton process. The efficiency of the electro-Fenton process was evaluated in the oxidation of Rhodamine B dye. To increase the efficiency of the electro-Fenton process, air was bubbled through the Fe_2O_3/GT perforated tubular graphite electrode at different pressures. At air pressures from 0.1 to 0.6 MPa, the electrode demonstrated an increased rate of the rhodamine B oxidation in the electro-Fenton process. Complete decolorization of the rhodamine B solution was achieved in 20 min of electrolysis at a pressure of 0.6 MPa. Carrying out the electro-Fenton process under air pressure also reduced the energy consumption.

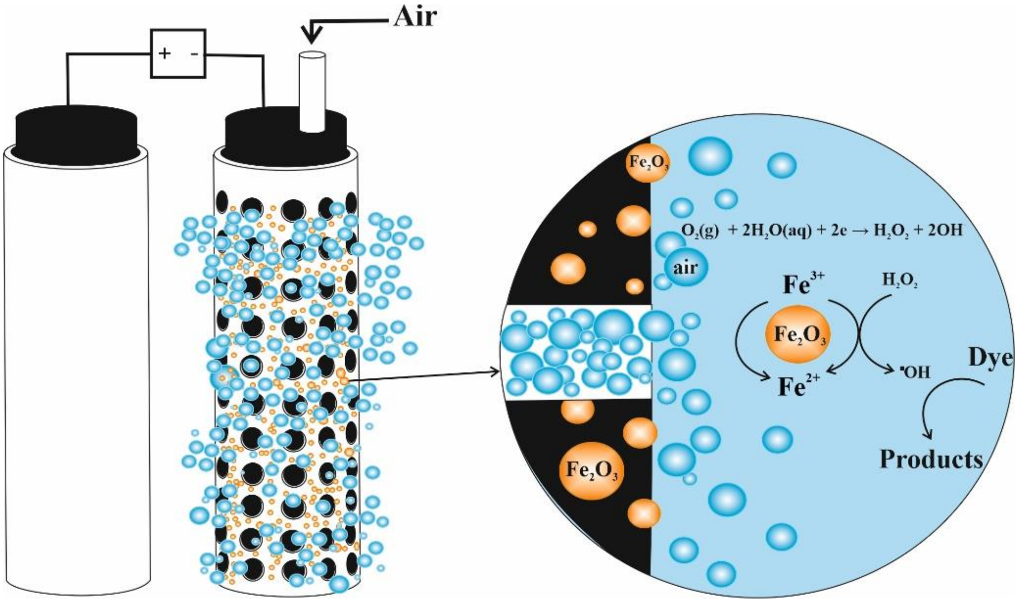

Figure 5 The scheme of the electro-Fenton process under air pressure using the Fe_2O_3/graphite perforated tubular electrode.

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Supplementary materials

No supplementary materials are available.

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Data availability statement

Data will be made available on request.

Author contributions

Conceptualization: A.I., Z.A.
Data curation: A.I.
Formal Analysis: A.I., Z.A., M.I.
Funding acquisition: A.I.
Investigation: A.I., Z.A., M.I.
Methodology: A.I., Z.A., M.I., T.A.
Project administration: A.I.
Resources: A.I., Z.A.
Software: A.I.
Supervision: A.I.
Validation: A.I., M.I.
Visualization: A.I., M.I.
Writing – original draft: Z.A., M.I., T.Kh.
Writing – review & editing: A.I., T.Kh.

Conflict of interest

The authors declare no conflict of interest.

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References

1. Ahmed S, Rasul MG, Martens WN, Brown R, Hashib MA. Advances in heterogeneous photocatalytic degradation of phenols and dyes in wastewater: A review. Water Air Soil Pollut. 2011;215:3–29. doi:10.1007/s11270-010-0456-3
2. Miklos DB, Remy C, Jekel M, Linden KG, Drewes JE, Hübner U. Evaluation of advanced oxidation processes for water and wastewater treatment – A critical review. Water Res. 2018;139:118–131. doi:10.1016/j.watres.2018.03.042
3. Singh J, Sharma S, Basu AS. Synthesis of Fe_2O_3/TiO_2 monoliths for the enhanced degradation of industrial dye and pesticide via photo-Fenton catalysis. J Photochem Photobiol A Chem. 2019;376:32–42. doi:10.1016/J.JPHOTOCHEM.2019.03.004.
4. Brillas E. Fenton, photo-Fenton, electro-Fenton, and their combined treatments for the removal of insecticides from waters and soils. A review. Sep Purif Technol. 2022;284:120290. doi:10.1016/J.SEPPUR.2021.120290
5. Verma M, Haritash AK. Review of advanced oxidation processes (AOPs) for treatment of pharmaceutical wastewater. Adv Environ Res. 2020;9:1–17. doi:10.12989/AER.2020.9.1.001
6. Gonzaga IMD, Almeida CVS, Mascaro LH. A Critical Review of Photo-Based Advanced Oxidation Processes to Pharmaceutical Degradation. Catalysts. 2023;13:221. doi:10.3390/CATAL13020221.
7. Yu S-Y, Xie Z-H, Yu Wu X, Zheng Y-Z, Shi Y, Xiong Z-K, Zhou P, Liu Y, He C-S, Pan Z-C, Wang K-J, Lai B. Review of Advanced Oxidation Processes for Treating Hospital Sewage to Achieve Decontamination and Disinfection. Chin Chem Lett. 2023;108714. doi:10.1016/J.CCLET.2023.108714
8. Orimolade BO, Oladipo AO, Idris AO, Usisipho F, Azizi S, Maaza M, Lebelo SL, Mamba BB Advancements in Electrochemical Technologies for the Removal of Fluoroquinolone Antibiotics in Wastewater: A Review. SciTotal Environm. 2023;881:163522. doi:10.1016/J.SCITOTENV.2023.163522
9. Holkar CR, Jadhav AJ, Pinjari DV, Mahamuni NM, Pandit AB. A Critical Review on Textile Wastewater Treatments: Possible Approaches. J Environ Manag. 2016;182:351–366. doi:10.1016/j.jenvman.2016.07.090
10. Nidheesh PV, Gandhimathi R, Ramesh ST. Degradation of Dyes from Aqueous Solution by Fenton Processes: A Review. Environ Sci Pollut Res. 2013;20 (4):2099–2132. doi:10.1007/S11356-012-1385-Z
11. Isaev AB, Magomedova AG. Advanced Oxidation Processes Based Emerging Technologies for Dye Wastewater Treatment. Moscow Univ Chem Bull. 2022;77 (4):181–196. doi:10.3103/S0027131422040046
12. Oturan MA, Aaron JJ. Advanced Oxidation Processes in Water/Wastewater Treatment: Principles and Applications. A Review. Crit Rev Environ Sci Technol. 2014;44(23):2577–2641. doi:10.1080/10643389.2013.829765
13. Wang Z, Liu M, Xiao F, Postole G, Zhao H, Zhao G. Recent Advances and Trends of Heterogeneous Electro-Fenton Process for Wastewater Treatment-Review. Chin Chem Lett. 2021. doi:10.1016/J.CCLET.2021.07.044
14. Ma D, Yi H, Lai C, Liu X, Huo X, An Z, Li L, Fu Y, Li B, Zhang M, Qin L, Liu S, Yang L. Critical Review of Advanced Oxidation Processes in Organic Wastewater Treatment. Chemosphere. 2021;275:130104. doi:10.1016/J.CHEMOSPHERE.2021.130104
15. Wang N, Zheng T, Zhang G, Wang P. A Review on Fenton-like Processes for Organic Wastewater Treatment. J Environ Chem Eng. 2016;4(1):762–787. doi:10.1016/J.JECE.2015.12.016
16. Poza-Nogueiras V, Rosales E, Pazos M, Sanromán MÁ. Current Advances and Trends in Electro-Fenton Process Using Heterogeneous Catalysts – A Review. Chemosphere. 2018;201:399–416. doi:10.1016/J.CHEMOSPHERE.2018.03.002
17. Drogui P, Blais J, Mercier G. Review of Electrochemical Technologies for Environmental Applications. Recent Patents Eng. 2007;1:257–272. doi:10.2174/187221207782411629
18. Gutiérrez MC, Crespi M. A Review of Electrochemical Treatments for Colour Elimination. Coloration Technol. 1999;115(11):342–345. doi:10.1111/J.1478-4408.1999.TB00323.X
19. Isaev AB, Shabanov NS, Magomedova AG, Nidheesh PV, Oturan MA. Electrochemical Oxidation of Azo Dyes in Water: A Review. Environ Chem Lett. 2023;21(5):2863–2911. doi:10.1007/s10311-023-01610-5
20. Garcia-Segura S, Ocon JD, Chong MN. Electrochemical Oxidation Remediation of Real Wastewater Effluents — A Review. Process Safety Environ Protect. 2018;113:48–67. doi:10.1016/j.psep.2017.09.014
21. Sirés I, Brillas E, Oturan MA, Rodrigo MA, Panizza M. Electrochemical Advanced Oxidation Processes: Today and Tomorrow. A Review. Environ Sci Pollut Res. 2014;21(14):8336–8367. doi:10.1007/S11356-014-2783-1
22. Brillas E, Martínez-Huitle CA. Decontamination of Wastewaters Containing Synthetic Organic Dyes by Electrochemical Methods. An Updated Review. Appl Catal B. 2015;166–167:603–643. doi:10.1016/J.APCATB.2014.11.016
23. Brillas E, Sirés I, Oturan MA. Electro-Fenton Process and Related Electrochemical Technologies Based on Fenton's Reaction Chemistry. Chem Rev. 2009;109(12):6570–6631. doi:10.1021/CR900136G

24. Chen X, Wang L, Jin J, Sun W, Yang Z, Chen X, Liu G. Bifunctional boron-nitrogen-containing graphite felt cathode for highly efficient treatment on dye wastewater depending on the metal-free electro-Fenton process. Separat Purificat Technol. 2024;347:127600. doi:10.1016/j.seppur.2024.127600
25. Cui Y, Yang H, Xiang X, Zhao S, Huang Q, Huang Z. TCE degradation of modified graphite felt cathode in a flow-through electro-Fenton system and its H_2O_2 production ability in a real contaminated field. Chem Eng J. 2024;489:151445. doi:10.1016/j.cej.2024.151445
26. Fang X, Feng Y, Li X, Ding D, Wang X, Zhang D. Efficient Fenton-like catalysis enabled by single cobalt atoms anchored on expanded graphite: Remarkable intrinsic activity of Co-N4 sites and the enhanced mass transfer facilitated by gradient mesopore structure. Chem Eng J. 2024;479:147840. doi:10.1016/j.cej.2023.147840
27. Kuleyin A, Gök A, Akbal F. Treatment of textile industry wastewater by electro-Fenton process using graphite electrodes in batch and continuous mode. J Environ Chem Eng. 2021;9(1):104782. doi:10.1016/j.jece.2020.104782
28. Guo H, Zhao C, Xu H, Zhang Y, Jiao Y, Hao H, Li N, Xu W. New insights into the slow-drying modified hydrophilic graphite felt gas-diffusion cathode using acetylene black/PTFE for efficient electro-Fenton removal of norfloxacin. J Indust Eng Chem. 2023;121:409–420. doi:10.1016/j.jiec.2023.01.043
29. Guo H, Zhao C, Xu H, Hao H, Yang Z, Li N, Xu W. Enhanced H_2O_2 formation and norfloxacin removal by electro-Fenton process using a surface-reconstructed graphite felt cathode: New insight into synergistic mechanism of defective active sites. Environ Res. 2023;220:115221. doi:10.1016/j.envres.2023.115221
30. Lv J, Zhao Q, Wang K, Jiang J, Ding J, Wei L. A critical review of approaches to enhance the performance of bio-electro-Fenton and photo-bio-electro-Fenton systems. J Environ Manag. 2024;365:121633. doi:10.1016/j.jenvman.2024.121633
31. Sun YM, Li C, Liu YH. CO_2-activated graphite felt as an effective substrate to promote hydrogen peroxide synthesis and enhance the electro-Fenton activity of graphite/Fe_3O_4 composites in situ fabricated from acid mine drainage. J Water Process Eng. 2024;57:104690. doi:10.1016/j.jwpe.2023.104690
32. Yan Z, Qi H, Shi X, Liu Z, Sun Z. Phosphorus doping to boost the electro-Fenton degradation of sulfamethoxazole using mixed-valence copper (I and II) phosphate/etched graphite felt cathode. Separation Purification Technol. 2024;339:126716. doi:10.1016/j.seppur.2024.126716
33. Rabiei M, Farhadian M, Solaimany Nazar AR, Tangestaninejad S. Integrated Electro-photo-Fenton process and visible light-driven TiO_2/rGO/Fe_2O_3 photocatalyst based on graphite cathode in the presence of iron anode for Metronidazole degradation. J Appl Electrochem. 2023;53(1):65–83. doi:10.1007/s10800-022-01760-4
34. Qi H, Shi X, Liu Z, Yan Z, Sun Z. In situ etched graphite felt modified with CuFe2O4/Cu2O/Cu catalyst derived from CuFe PBA for the efficient removal of sulfamethoxazole through a heterogeneous electro-Fenton process. Appl Catalysis B Environ. 2023;331:122722. doi:10.1016/j.apcatb.2023.122722
35. Cui L, Sun M, Zhang Z. Flow-through integration of FeOCl/graphite felt-based heterogeneous electro-Fenton and Ti_4O_7-based anodic oxidation for efficient contaminant degradation. Chem Eng J. 2022;450:138263. doi:10.1016/j.cej.2022.138263
36. Chen S, Cheng C. Facile preparation of iron-anchored graphite cloth through salt immersion and sintering approaches and its application to the electro-Fenton catalytic system as a cathode. Chem Papers. 2022;76(10);6427–6435. doi:10.1007/s11696-022-02258-1
37. Liu P, Zhong D, Xu Y, Zhong N, He G. Co/Fe co-doped porous graphite carbon derived from metal organic framework for microelectrolysis-Fenton catalytic degradation of Rhodamine B. J Environ Chem Eng. 2021;9(5):105924. doi:10.1016/j.jece.2021.105924
38. Li B, Sun JD, Tang C, Yan ZY, Zhou J, Wu XY, Yong XY. A novel core-shell Fe@Co nanoparticles uniformly modified graphite felt cathode (Fe@Co/GF) for efficient bio-electro-Fenton degradation of phenolic compounds. Sci Total Environ. 2021;760:143415. doi:10.1016/j.scitotenv.2020.143415
39. Magomedova A, Isaev A, Orudzhev F. Oxygen Vacancies Enhanced Photo-Fenton-like Catalytic Degradation of Rhodamine B by Electrochemical Synthesized α-Fe_2O_3 Nanoparticles. Inorg Chem Commun. 2024;165:112563. doi:10.1016/J.INOCHE.2024.112563
40. Magomedova A, Isaev A, Orudzhev F, Sobola D, Murtazali R, Rabadanova A, Shabanov NS, Zhu M, Emirov R, Gadzhimagomedov S, Alikhanov N, Kasinathan K. Magnetically Separable Mixed-Phase α/γ-Fe_2O_3 Catalyst for Photo-Fenton-like Oxidation of Rhodamine B Catalysts. 2023;13 (5):872. doi:10.3390/CATAL13050872
41. El Aggadi S, Kaichouh G, El Abbassi Z, Fekhaoui M, Hourch A. EL. Electrode Material in Electrochemical Decolorization of Dyestuffs Wastewater: A Review. E3S Web Conf. 2021;234:00058. doi:10.1051/e3sconf/202123400058
42. Krishnan S, Martínez-Huitle CA, Nidheesh PV. An Overview of Chelate Modified Electro-Fenton Processes. J Environ Chem. Eng. 2022;10(2):107183. doi:10.1016/j.jece.2022.107183
43. Li D, Yang T, Liu Z, Xia Y, Chen Z, Yang S, Chao Gai, Amit Bhatnagar, Yun Hau Ng, Ok YS. Green synthesis of graphite-based photo-Fenton nanocatalyst from waste tar via a self-reduction and solvent-free strategy. Sci Total Environ. 2022;824:153772. doi:10.1016/j.scitotenv.2022.153772
44. Divyapriya G, Nidheesh PV. Importance of Graphene in the Electro-Fenton Process. ACS Omega. 2020;5(10):4725–4732. doi:10.1021/acsomega.9b04201
45. Oturan N, Oturan MA. Electro-Fenton Process: Background, New Developments, and Applications. Electrochem Water Wastewater Treatment. 2018;193–221. doi:10.1016/B978-0-12-813160-2.00008-0
46. Matyszczak G, Krzyczkowska K, Fidler A. A Novel, Two-Electron Catalysts for the Electro-Fenton Process. J Water Process Eng. 2020;36:101242. doi:10.1016/J.JWPE.2020.101242
47. Li L, Hu H, Teng X, Yu Y, Zhu Y, Su X. Electrogeneration of H_2O_2 using a Porous Hydrophobic Acetylene Black Cathode for Electro-Fenton Process. Chem Eng Process Process Intensificat. 2018;133(2):34–39. doi:10.1016/j.cep.2018.09.013
48. Hu Xu, Hongkai Guo, Changsheng Chai, Na Li, Xueyong Lin, Weijun Xu. Anodized graphite felt as an efficient cathode for in-situ hydrogen peroxide production and Electro-Fenton degradation of rhodamine B. 2022;131936. doi:10.1016/j.chemosphere.2021.131936
49. Nidheesh PV, Ganiyu SO, Martínez-Huitle CA, Mousset E, Olvera-Vargas H, Trellu C, Zhou M, Oturan MA. Recent Advances in Electro-Fenton Process and Its Emerging Applications. Crit Rev Environ Sci Technol. 2022;1–27. doi:10.1080/10643389.2022.2093074
50. Nidheesh PV, Gandhimathi R. Removal of Rhodamine B from Aqueous Solution Using Graphite–Graphite Electro-Fenton System. Desalinat Water Treatment. 2014;52(10–12):1872–1877. doi:10.1080/19443994.2013.790321
51. Ren W, Peng Q, Huang Z, Zhang Z, Zhan W, Lv K, Sun J. Effect of Pore Structure on the Electro-Fenton Activity of ACF@OMC Cathode. Ind Eng Chem Res. 2015;54(34):8492–8499. doi:10.1021/acs.iecr.5b02139
52. Pérez JF, Sabatino S, Galia A, Rodrigo MA, Llanos J, Sáez C, Scialdone O. Effect of Air Pressure on the Electro-Fenton Process at Carbon Felt Electrodes. Electrochim Acta. 2018;273:447–453. doi:10.1016/J.ELECTACTA.2018.04.031
53. Panizza M, Oturan MA. Degradation of Alizarin Red by Electro-Fenton Process Using a Graphite-Felt Cathode. Electrochim Acta. 2011;56(20):7084–7087. doi:10.1016/j.electacta.2011.05.105

54. Wu X, Yang X, Wu D, Fu R. Feasibility Study of Using Carbon Aerogel as Particle Electrodes for Decoloration of RBRX Dye Solution in a Three-Dimensional Electrode Reactor. Chem Eng J. 2008;138(1–3):47–54. doi:10.1016/J.CEJ.2007.05.027
55. Nidheesh PV;Gandhimathi R. Trends in Electro-Fenton Process for Water and Wastewater Treatment: An Overview. Desalinat. 2012;299:1–15. doi:10.1016/j.desal.2012.05.011
56. Nidheesh PV, Trellu C, Vargas HO, Mousset E, Ganiyu SO, Oturan MA. Electro-Fenton Process in Combination with Other Advanced Oxidation Processes: Challenges and Opportunities. Curr Opin Electrochem. 2023;37:101171. doi:10.1016/J.COELEC.2022.101171
57. Mukherjee R, Kumar R, Sinha A, Lama Y, Saha AK. A Review on Synthesis, Characterization, and Applications of Nano Zero Valent Iron (NZVI) for Environmental Remediation. Crit Rev Environ Sci Technol. 2016;443–466. doi:10.1080/10643389.2015.1103832
58. Nidheesh PV, Gandhimathi R. Comparative Removal of Rhodamine B from Aqueous Solution by Electro-Fenton and Electro-Fenton-Like Processes. Clean. 2014;42(6):779–784. doi:10.1002/CLEN.201300093
59. Gopinath A, Pisharody L, Popat A, Nidheesh PV. Supported Catalysts for Heterogeneous Electro-Fenton Processes: Recent Trends and Future Directions. Curr Opin Solid State Mater Sci. 2022;26(2):100981. doi:10.1016/J.COSSMS.2022.100981
60. Huang LZ, Zhu M, Liu Z, Wang Z, Hansen HCB. Single Sheet Iron Oxide: An Efficient Heterogeneous Electro-Fenton Catalyst at Neutral pH. J Hazard Mater. 2019;364:39–47. doi:10.1016/j.jhazmat.2018.10.026
61. Lin L, Zhang F, Hou X, Wang L, Wu W, Wang L, Li Y, Xie H. Fe@Fe_2O_3/Etched Carbon Felt as a Cathode for Efficient Bisphenol a Removal in a Flow-through Electro-Fenton System: Electron Transfer Pathway and Underlying Mechanism. Sep Purif Technol. 2024;334:125982. doi:10.1016/J.SEPPUR.2023.125982
62. Qi H, Sun X, Sun Z. Cu-Doped Fe_2O_3 Nanoparticles/Etched Graphite Felt as Bifunctional Cathode for Efficient Degradation of Sulfamethoxazole in the Heterogeneous Electro-Fenton Process. Chem Eng J. 2022;427:131695. doi:10.1016/J.CEJ.2021.131695
63. García-Rodríguez O, Bañuelos JA, El-Ghenymy A, Godínez LA, Brillas E, Rodríguez-Valadez FJ. Use of a Carbon Felt-Iron Oxide Air-Diffusion Cathode for the Mineralization of Malachite Green Dye by Heterogeneous Electro-Fenton and UVA Photoelectro-Fenton Processes. J Electroanal Chem. 2016;767:40–48. doi:10.1016/j.jelechem.2016.01.035
64. El-Ghenymy A, Centellas F, Rodríguez RM, Cabot PL, Garrido JA, Sirés I, Brillas E. Comparative Use of Anodic Oxidation, Electro-Fenton and Photoelectro-Fenton with Pt or Boron-Doped Diamond Anode to Decolorize and Mineralize Malachite Green Oxalate Dye. Electrochim Acta. 2015;182:247–256. doi:10.1016/j.electacta.2015.09.078
65. García-Rodríguez O, Bañuelos JA, El-Ghenymy A, Godínez LA, Brillas E, Rodríguez-Valadez FJ. Use of a Carbon Felt–Iron Oxide Air-Diffusion Cathode for the Mineralization of Malachite Green Dye by Heterogeneous Electro-Fenton and UVA Photoelectro-Fenton Processes. J Electroanal Chem. 2016;767:40–48. doi:10.1016/J.JELECHEM.2016.01.035
66. El-Ghenymy A, Centellas F, Rodríguez RM, Cabot PL, Garrido JA, Sirés I, Brillas E. Comparative Use of Anodic Oxidation, Electro-Fenton and Photoelectro-Fenton with Pt or Boron-Doped Diamond Anode to Decolorize and Mineralize Malachite Green Oxalate Dye. Electrochim Acta. 2015;182:247–256. doi:10.1016/J.ELECTACTA.2015.09.078
67. Ai Z, Lu L, Li J, Zhang L, Qiu J, Wu M. Fe@Fe_2O_3 Core-Shell Nanowires as Iron Reagent. 1. Efficient Degradation of Rhodamine by a Novel Sono-Fenton Process. J Phys Chem C. 2007;111(11):4087–4093. doi:10.1021/jp065559l
68. Ai Z, Lu L, Li J, Zhang L, Qiu J, Wu M. Fe@Fe_2O_3 Core-Shell Nanowires as the Iron Reagent. 2. An Efficient and Reusable Sono-Fenton System Working at Neutral PH. J Phys Chem C. 2007;111(20):7430–7436. doi:10.1021/jp070412v
69. Wang CT, Chou WL, Chung MH, Kuo YM. COD Removal from Real Dyeing Wastewater by Electro-Fenton Technology Using an Activated Carbon Fiber Cathode. Desalination. 2010;253(1–3):129–134. doi:10.1016/j.desal.2009.11.020
70. Zhang C, Ren G, Wang W, Yu X, Yu F, Zhang Q, Zhou M. A New Type of Continuous-Flow Heterogeneous Electro-Fenton Reactor for Tartrazine Degradation. Sep Purif Technol. 2019;208:76–82. doi:10.1016/J.SEPPUR.2018.05.016
71. Ren G, Zhou M, Su P, Yang W, Lu X, Zhang Y. Simultaneous Sulfadiazines Degradation and Disinfection from Municipal Secondary Effluent by a Flow-through Electro-Fenton Process with Graphene-Modified Cathode. J. Hazard Mater. 2019;368:830–839. doi:10.1016/J.JHAZMAT.2019.01.109
72. Liu HY, Jiang J, Tang L, Liang Y, Xue SG. Recent Progress in Electrocatalytic Selectivity in Heterogeneous Electro-Fenton Processes. J Mater Chem A Mater. 2023;11(14):7387–7408. doi:10.1039/D2TA09676E
73. Esteves BM, Rodrigues CSD, Madeira LM. Wastewater Treatment by Heterogeneous Fenton-like Processes in Continuous Reactors. Handbook Environ Chem. 2019;67:211–255. doi:10.1007/698_2017_81
74. Martínez-Huitle CA, Rodrigo MA, Sirés I, Scialdone O. Single and Coupled Electrochemical Processes and Reactors for the Abatement of Organic Water Pollutants:A Critical Review. Chem Rev. 2015;115(24):13362–13407. doi:10.1021/ACS.CHEMREV.5B00361
75. Isaev AB, Aliev ZM. Effect of oxygen pressure on the electrochemical oxidation of Chrome Brown azo dye. Russ J Appl Chem. 2012;85:776-781. doi:10.1134/S1070427212050163
76. Dinesh A, Anantha MS, Santosh MS, Priya MG, Venkatesh K, Yogesh Kumar KS, Raghu MS, Muralidhara HB. Improved Performance of Iron-Based Redox Flow Batteries Using WO_3 Nanoparticles Decorated Graphite Felt Electrode. Ceram Int. 2021;47 (7):10250–10260. doi:10.1016/J.CERAMINT.2020.09.225
77. Nayak PK. Comment on “Phase Analysis of Iron Oxides Forming the Red Pigment Layer of the Ancient Earthenwares Excavated from the Southern Korean Peninsula.” J Radioanal Nucl Chem. 2022;331(3):1519–1520. doi:10.1007/S10967-021-08181-1
78. Premila M, Rajaraman R, Abhaya S, Govindaraj R, Amarendra G. Atmospheric Corrosion of Boron Doped Iron Phosphate Glass Studied by Raman Spectroscopy. J Non Cryst Solids. 2020;530:119748. doi:10.1016/J.JNONCRYSOL.2019.119748
79. Qiu S He D, Ma J, Liu T, Waite TD. Kinetic Modeling of the Electro-Fenton Process: Quantification of Reactive Oxygen Species Generation. Electrochim Acta. 2015;176:51–58. doi:10.1016/j.electacta.2015.06.103
80. Nidheesh PV, Gandhimathi R, Sanjini NS. $NaHCO_3$ Enhanced Rhodamine B Removal from Aqueous Solution by Graphite-Graphite Electro Fenton System. Sep Purif Technol. 2014;132:568–576. doi:10.1016/j.seppur.2014.06.009
81. Scialdone O, Galia A, Gattuso C, Sabatino S, Schiavo B. Effect of Air Pressure on the Electro-Generation of H2O2 and the Abatement of Organic Pollutants in Water by Electro-Fenton Process. Electrochim Acta. 2015;182:775–780. doi:10.1016/J.ELECTACTA.2015.09.109
82. Qi H, Ren W, Shi X, Sun Z. Hydrothermally modified graphite felt as the electro-Fenton cathode for effective degradation of diuron: The acceleration of Fe^{2+} regeneration and H_2O_2 production. Separat Purificat Technol. 2022;299:121724. doi:10.1016/j.seppur.2022.121724
83. Gomathi E, Maharaja P, Rathore HS, Boopathy R, Panda RC, Senthilvelan T, Arthanareeswari M. Treatment of textile dye consortium through photo-electro-fenton process using graphite-Ti electrode system and toxicity studies. Carbon Lett. 2023;33(7):2011-2025. doi:10.1007/s42823-023-00551-x