Fenton-like Degradation of Phenol Catalyzed by a Series of Fe-Containing Mixed Oxides Systems

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Abstract: In our attempts to develop a solid catalyst to degrade organic pollutants in wastewater via the Fenton-like reaction, six Fe-containing mixed oxide systems were prepared by means of the sol-gel auto-combustion method to have the following stoichiometries: CuFe1.2O2.8, BaFe7.2O11.8, BaFe7.2Cu2O13.8, BaFe5.4V3O16.6, BaFe4.8Cu2V3O17.7 and Ag2Fe5.4V3O16.6. The prepared systems were thermally treated at 550°C, 650°C, 800°C and 1100°C, and then characterized by XRD to identify the present phases. The systems were tested with respect to their catalytic efficiency in the degradation of phenol (200 ppm) in water where CuFe1.2O2.8 was found to be the most reactive one (80% removal in 60 min). It showed thereby first-order kinetics and an enhanced behavior under irradiation with a 30-W LED light source. The positive role of irradiation was most obvious in the case of Ag2Fe5.4V3O16.6 in which almost complete conversion was achieved in 120 min compared to only 45% in the same period but without irradiation. However, increasing the temperature at which thermal treatment is performed was found to suppress the catalytic activity of the system. Due to their high efficiency and rather low leaching rates of constituents, CuFe1.2O2.8 or Ag2Fe5.4V3O16.6 seem to be very promising in the Fenton-like degradation of organic pollutants.

Keywords: Degradation of Organic Pollutants, Fenton Reaction, Phenol, Iron oxide, Advanced Oxidation Processes, Peroxide Oxidation.

1. Introduction

Advanced Oxidation Processes (AOP) represent a class of attractive and promising wastewater treatment methods based on the oxidation of organic pollutants by \textit{in-situ} generated hydroxyl radicals. They are appealing because of the possibility to gain complete oxidation or mineralization of organic contaminants through a process that operates near ambient temperature and pressure [1]. Hydrogen peroxide can thereby be used as a powerful oxidant and the classical Fenton reaction catalyzed by Fe$^{2+}$ ions can be used to decompose it generating the desired hydroxyl radicals. The process is highly efficient, rather simple and H$_2$O$_2$ is non-toxic [2-7]. It suffers however from several drawbacks including the high operational cost, difficulties in recycling the catalyist (Fe$^{2+}$), the limited pH range of operation (optimum at pH 3) and the large volume of iron sludge produced [8, 9]. One way to overcome these disadvantages is by the application of heterogeneous catalysts that can mediate the Fenton reaction over a wide pH range with limited leaching into solution and can be easily separated from the reaction mixture and then recycled [10, 11]. Moreover, irradiation can also elevate the reaction efficiency and in the past two decades, interest in the replacement of UV radiation with solar energy in wastewater treatment increased [12]. Nevertheless, heterogeneous catalysts show lower rates of oxidation when compared to the homogeneous reaction due to the small number of active sites at the catalyst surface, the reason why intensive research is being conducted to develop highly active solid catalysts for this purpose [13].
A wide variety of solid materials have been tested as Fenton catalysts among which iron based systems gained great attention. The latter vary in shape and form from zero-valent iron [14,15], iron oxides [16,17], to clay supported catalysts [11,18]. Modification of such systems has also been attempted, for example, by doping with sulfur [19] or by \textit{in-situ} growing of a Fe$_3$O$_4$/SiO$_2$ ceramic coating on a metal substrate to maintain its strong mechanical adhesion for repeated use [20]. Exploitation of some industrial waste products, such as coal fly ash, to catalyze the Fenton reaction has been also reported where the catalytic activity of coal fly ash has been attributed to its content of Fe [21,22]. Ferrites were also widely investigated [12 and references therein]. The redox properties of the ferrites are strongly affected by the presence of different metals in the lattice structure, their nature, sites and amounts [23-25]. Ferrites have also the merit of a band gap capable of absorbing visible light and enhanced efficiency due to the available extra catalytic sites [26]. In virtue of their magnetic properties, they can also be easily separated [27]. Baldrain et al. reported the decolorization of a variety of dyes by hydrogen peroxide over MO-Fe$_2$O$_3$ mixed oxide catalysts (spinel ferrites) with M= Fe, Cu, Co, Mn [28]. Systems such as Fe$_{2.25}$Co$_{0.75}$O$_4$ and Fe$_{2.47}$Mn$_{0.53}$O$_4$ have been reported to be very efficient (99% removal) in the degradation of methylene blue [23]. Another type of an iron containing mixed oxide, namely BiFeO$_3$ with perovskite structure, was shown to achieve 75% degradation of Rhodamine B in 90 min in dark [29].

In this work, six Fe-containing mixed oxide systems, CuFe$_{1.2}$O$_{2.8}$, BaFe$_{7.2}$O$_{11.8}$, BaFe$_{7.2}$Cu$_{2}$O$_{13.8}$, BaFe$_{5.4}$V$_{3}$O$_{16.6}$, BaFe$_{4.8}$Cu$_{2}$V$_{3}$O$_{17.7}$ and Ag$_2$Fe$_{5.4}$V$_{3}$O$_{16.6}$, were prepared, characterized and investigated with respect to their efficiency in the Fenton-like degradation of phenol, a typical bio-refractory compound with high toxicity level and can therefore be used as a model of such contaminations in industrial wastewater.

2. Experimental:

The mixed oxide systems have been prepared via the sol-gel auto-combustion method to have the following stoichiometries: CuFe$_{1.2}$O$_{2.8}$, BaFe$_{7.2}$O$_{11.8}$, BaFe$_{7.2}$Cu$_{2}$O$_{13.8}$, BaFe$_{5.4}$V$_{3}$O$_{16.6}$, BaFe$_{4.8}$Cu$_{2}$V$_{3}$O$_{17.7}$ and Ag$_2$Fe$_{5.4}$V$_{3}$O$_{16.6}$. Fe(NO$_3$)$_3$.9H$_2$O (Alfa Aesar), Cu(NO$_3$)$_2$.4H$_2$O (BDH), NH$_4$VO$_3$ (Riedel-deHaën), CH$_3$COOAg (PHARMACOS LTD), Ba(NO$_3$)$_2$.2H$_2$O (BDH) and citric acid (AVONCHEM) were used as starting materials. The sol was prepared by dissolving the proper ratio of metal nitrates and ammonium metavanadate in 100 ml of water. Citric Acid (CA) with a 3:1 CA/Fe$_3^+$ molar ratio was separately dissolved in minimum amount of water. The two solutions were then combined and heated to reach a temperature of 80°C. The pH was adjusted to 8 using aqueous ammonia solution (Xllong chemical Industry) before heating on a hot plate for few hours with constant stirring during which the water content was reduced continuously by evaporation, thus, increasing the viscosity of the sol and indicating gel formation. The gel was left overnight. Next day, it was heated on the hot plate until auto-ignition started forming loose powder. The prepared systems were thermally treated for 4 hours at 550°C under flowing oxygen and at 650°C, 800°C and 1100°C under open atmosphere. The prepared systems are designated by their composition followed by the temperature at which thermal treatment has been carried out, for example, CuFe$_{1.2}$O$_{2.8}$-550 and Ag$_2$Fe$_{5.4}$V$_{3}$O$_{16.6}$-800. All systems were characterized with respect to their structure by X-ray diffraction (XRD) using a Shimadzu LabX device with a Cu-K$_\alpha$-tube ($\lambda$=1.5418 Å) in the range of 2θ=20°-20-80° with a scanning rate of 0.5°/min.

The reaction system for the phenol degradation consists of a 500-ml conical flask, magnetic stirrer (STUAART Scientific Co), peristaltic pump (Gilson-Model 312), a temperature controlled water bath (MA 6 LAUDA and B LAUDA) and an LED (30W, NWELIHT, IP66) as a light source. In a typical experiment, 0.25 g catalyst is added to 250 mL of 200 ppm aqueous phenol solution (CDH laboratory Reagent). The reaction solution is stirred at constant temperature (313 K) for 15
minutes. A zero-time sample is withdrawn before the continuous addition of 3% hydrogen peroxide solution (GFS CHEMICALS) is started by means of the peristaltic pump at a flow rate of 20 mL/h. If applied, the reaction solution is exposed perpendicularly to the light produced by the LED source positioned 30 cm above the reaction vessel. The progress of reaction was monitored by high-performance liquid chromatography, HPLC, (Dionex, Ultimate 3000 LC System) equipped with a variable wavelength detector. Samples were withdrawn every 30 min and immediately centrifuged to remove suspended particles. The analysis method was as follows: 250×4.6 C-18 column; mobile phase 60% methanol - 40% water at a flow rate of 1.20 mL/min with constant wavelength detection at 270 nm.

3. Results and Discussion

3.1. X-ray Diffraction

Figure 1 represents the XRD patterns of CuFe1.2O2.8-U, CuFe1.2O2.8-550, CuFe1.2O2.8-650, CuFe1.2O2.8-800 and CuFe1.2O2.8-1100. The major diffraction lines coincide with those of tetragonal CuFe2O4 as indicated by the red vertical lines of the standard pattern (JCPDS 00-034-0425). The tetragonal phase is the more stable Cu ferrite phase [30]. A deficiency of Cu2+ cations in the B sublattice leads however to the absence of cooperative Jahn-Teller distortion and thus to the transformation of the crystal phase into a cubic one [31], but no indication for formation the cubic phase is obvious in figure 1 (black vertical lines corresponding to the standard pattern JCPDS 00-025-0238). The presence of monoclinic copper (II) oxide is confirmed by the diffraction lines at 38.9, 48.6° and the shoulder at ~35.6° coinciding with those of CuO standard pattern (JCPDS 00-045-0937) as indicated by the blue vertical lines in Figure 1. Figure 1 shows also that as the temperature at which the thermal treatment was performed is increased, the diffraction lines become sharper corresponding to increased degree of crystallinity.

Figure 2 represents the XRD patterns of Ag2Fe5.4V3O16.6-U, Ag2Fe5.4V3O16.6-550, Ag2Fe5.4V3O16.6-650, Ag2Fe5.4V3O16.6-800 and Ag2Fe5.4V3O16.6-1100. The major diffraction lines coincide with those of α-Fe2O3 as indicated by the black vertical lines of the standard pattern (JCPDS card 00-033-0664) in the Figure. A series of diffraction features most obvious in the 20-range 25-32° seem to belong to a divanadate phase. Due to the non-availability of XRD reference patterns for barium or iron vanadate, the reference pattern (red vertical lines) for Mg2V2O7 (JCPDS card 00-031-0816) was inserted in the figure with the purpose of identifying the divanadate phase. The good agreement in the positions of the diffraction lines of Mg2V2O7 with those experimentally observed in the 20-range 25-32° makes us believe that iron is incorporated in this divanadate phase because the ionic radius of Fe2+ (0.780 Å) is closer to that of Mg2+ (0.720 Å) than Ba2+ (1.35 Å). The divanadate diffraction features are however not pronounced in the thermally untreated samples. As the temperature at which the thermal treatment has been performed is raised (especially ≥ 650°C), the diffraction lines of both phases (α-Fe2O3 and divanadate) become sharper and more pronounced indicating increased crystallinity and crystal growth. In addition, crystalline orthorhombic V2O5 can be recognized to be present, especially after thermal treatment at 650°C or higher temperatures (diffraction patterns c-e in Figure 2), as indicated by the vertical blue lines of the standard (JCPDS card 00-045-1074). Below 650°C (i.e. in Ag2Fe5.4V3O16.6-550), tetragonal V2O5 (JCPDS card 00-041-1426) is the dominant vanadium(V) oxide phase. For the purpose of clarity, its main diffraction lines are assigned by asterisks in Figure 2. The results of the XRD characterization of the other systems are summarized in Table 1.
Table 1: Summary of XRD characterization of the investigated systems.

| System                  | Dominant Phase(s)                  | Minor Phase(s)                          |
|-------------------------|------------------------------------|-----------------------------------------|
| BaFe$_{7.2}$O$_{11.8}$-U | $\gamma$-Fe$_2$O$_3$ (maghemite)   | BaO                                     |
| BaFe$_{7.2}$O$_{11.8}$-550|                                    | BaO                                     |
| BaFe$_{7.2}$O$_{11.8}$-650| M-type Ba-hexaferrite               | $\alpha$-Fe$_2$O$_3$ (hematite); orthorhombic BaFe$_2$O$_4$ |
| BaFe$_{7.2}$O$_{11.8}$-800|                                    |                                         |
| BaFe$_{7.2}$O$_{11.8}$-1000|                                    |                                         |
| BaFe$_{7.2}$Cu$_{2}$O$_{13.8}$-U; -550; -650; -800 | M-type Ba-hexaferrite orthorhombic BaFe$_2$O$_4$ cubic CuFe$_2$O$_4$ monoclinic CuO | $\alpha$-Fe$_2$O$_3$ (hematite) |
| BaFe$_{5.4}$V$_{3}$O$_{16.6}$-U; -550; -650; -800 | $\alpha$-Fe$_2$O$_3$ (hematite) divanadate |  |
| BaFe$_{4.8}$Cu$_{2}$V$_{3}$O$_{17.7}$-U; -550; -800 | $\alpha$-Fe$_2$O$_3$ (hematite) divanadate | Orthorhombic V$_2$O$_5$ orthovanadate |

Fig. 1: XRD patterns of a) CuFe$_{1.2}$O$_{2.8}$-U, b) CuFe$_{1.2}$O$_{2.8}$-550, c) CuFe$_{1.2}$O$_{2.8}$-650, d) CuFe$_{1.2}$O$_{2.8}$-800 and e) CuFe$_{1.2}$O$_{2.8}$-1100. The vertical lines correspond to the standard patterns of tetragonal CuFe$_2$O$_4$ (red), cubic CuFe$_2$O$_4$ (black) and monoclinic CuO (blue).
3.2. Phenol degradation

Figure 3 represents the progress of phenol degradation over the thermally untreated forms of all six systems with (right) and without irradiation (left). Without irradiation, CuFe$_{1.2}$O$_{2.8}$-U (thermally Untreated) is by far the most active system accomplishing 95% degradation in two hours. This high activity of CuFe$_{1.2}$O$_{2.8}$-U can be correlated with the dominance of the spinel copper ferrite phase reported to show a rather high activity in the degradation of phenol [32]. On the other hand, BaFe$_{7.2}$O$_{11.8}$-U seems to be completely inactive. The partial substitution of Fe(III) by Cu(II) does not help much as only a slight decrease in the phenol concentration is observed after 180 min (BaFe$_{7.2}$Cu$_{2}$O$_{13.8}$-U). It is however obvious from Figure 3 that incorporating vanadium(V) in the system has a positive effect and the best behavior for the thermally untreated systems was observed for BaFe$_{4.8}$Cu$_{2}$V$_{3}$O$_{17.7}$ achieving almost 90% conversion in 150 min. The higher efficiency of BaFe$_{4.8}$Cu$_{2}$V$_{3}$O$_{17.7}$ compared to BaFe$_{5.4}$V$_{3}$O$_{16.6}$ reflects the importance of having Cu(II) ions incorporated in the system.
An important aspect of the degradation profile seen in Figure 3 is its sigmoidal shape most obvious in the case of CuFe\textsubscript{1.2}O\textsubscript{2.8} and BaFe\textsubscript{4.8}Cu\textsubscript{2}V\textsubscript{3}O\textsubscript{17.7} where the degradation of phenol does not start immediately and the concentration of phenol drops only slowly at the beginning of reaction characterizing a so-called induction period. This behavior is typical for a consecutive reaction and suggests that in the first step an active intermediate -in this case the hydroxyl radical as proposed by several studies [33-36]- is produced before it attacks in the second step the phenol molecules initiating thus its degradation. The extension of the induction period reflects thus how fast the hydroxyl radical is produced; the shorter the induction period, the more active the catalyst is.

Upon irradiation with a 30-W LED source (emitted radiation 400-750 nm) situated 30 cm from the reaction vessel, the catalytic performance of CuFe\textsubscript{1.2}O\textsubscript{2.8} has been improved as evidenced by the disappearance of the induction period as well as by the higher conversions achieved in a shorter time (> 96% in 90 min). The positive role of irradiation was most obvious in the case of Ag\textsubscript{2}Fe\textsubscript{5.4}V\textsubscript{3}O\textsubscript{16.6} in which almost complete conversion was achieved in 120 min compared to only 45% in the same period but without irradiation. Also in the case of Ag\textsubscript{2}Fe\textsubscript{5.4}V\textsubscript{3}O\textsubscript{16.6} the induction period disappears indicating the high production rate of the hydroxyl radicals. Whereas the catalytic activity of BaFe\textsubscript{7.2}Cu\textsubscript{2}O\textsubscript{13.8} and BaFe\textsubscript{7.2}O\textsubscript{11.8} was not affected by irradiation, that of BaFe\textsubscript{4.8}Cu\textsubscript{2}V\textsubscript{3}O\textsubscript{17.7} was suppressed. One possible explanation for this unexpected behavior is that irradiation enhances the decomposition of hydrogen peroxide but in an undesired way. In a previous study [37], it was concluded that parallel to the hydroxyl radical formation, H\textsubscript{2}O\textsubscript{2} may decompose in an undesired route yielding oxygen and that catalysts active in the latter route do not achieve high phenol degradation rates.

Figure 4 shows that beyond the induction period, the phenol degradation obeys first-order kinetics regardless whether the reaction system was irradiated or not. This is in agreement with literature reports [38] as well as kinetic models for the heterogeneously catalyzed degradation of phenol [39]. A closer look in Figure 4, for example to the effect of LED radiation on the activity of CuFe\textsubscript{1.2}O\textsubscript{2.8} of 550, indicates that irradiation not only decreases the extent of the induction period but increases also the first-order rate constant of degradation by almost 50% from 0.031 min\textsuperscript{-1} to 0.046 min\textsuperscript{-1}. This is in agreement with literature reports [38] as well as kinetic models for the heterogeneously catalyzed degradation of phenol [39]. A closer look in Figure 4, for example to the effect of LED radiation on the activity of CuFe\textsubscript{1.2}O\textsubscript{2.8} of 550, indicates that irradiation not only decreases the extent of the induction period but increases also the first-order rate constant of degradation by almost 50% from 0.031 min\textsuperscript{-1} to 0.046 min\textsuperscript{-1}.
0.048 min\(^{-1}\) suggesting an increased concentration of the hydroxyl radicals. The same trend has been also observed in the other systems CuFe\(_{1.2}\)O\(_{2.8}\)-U and Ag\(_2\)Fe\(_5\)V\(_3\)O\(_{16.6}\)-U, BaFe\(_{4.8}\)Cu\(_2\)V\(_3\)O\(_{17.7}\)-U being thereby an exception as discussed above.

The effect of temperature at which the thermal treatment was performed on the catalyst efficiency in the degradation of phenol is shown in Figure 5 for the CuFe\(_{1.2}\)O\(_{2.8}\) as an example. In general, the activity decreases as the thermal treatment temperature is increased but the CuFe\(_{1.2}\)O\(_{2.8}\)-1100 represents an exception to the observed trend as its activity is larger than that of CuFe\(_{1.2}\)O\(_{2.8}\)-800. Under irradiation, the same general trend has been observed (CuFe\(_{1.2}\)O\(_{2.8}\)-U ≈ CuFe\(_{1.2}\)O\(_{2.8}\)-550 > CuFe\(_{1.2}\)O\(_{2.8}\)-650 > CuFe\(_{1.2}\)O\(_{2.8}\)-1100 > CuFe\(_{1.2}\)O\(_{2.8}\)-800). Again, the activity of CuFe\(_{1.2}\)O\(_{2.8}\)-1100 is larger than that of CuFe\(_{1.2}\)O\(_{2.8}\)-800. The other systems follow also in general that trend with exceptions, for example BaFe\(_{4.8}\)Cu\(_2\)V\(_3\)O\(_{17.7}\)-U > BaFe\(_{4.8}\)Cu\(_2\)V\(_3\)O\(_{17.7}\)-550 ≈ BaFe\(_{4.8}\)Cu\(_2\)V\(_3\)O\(_{17.7}\)-650 > BaFe\(_{4.8}\)Cu\(_2\)V\(_3\)O\(_{17.7}\)-800. Although systems treated thermally at higher temperatures are usually expected to be less active than the corresponding ones treated at lower temperatures due to surface area loss [40] and consequently active sites loss [41], previous studies in our laboratories show that the Ni\(_x\)Cu\(_{1-x}\)Fe\(_2\)O\(_4\) systems thermally treated at 800°C were more active in the phenol degradation than when treated at 400°C despite the fact that the latter were much more active in the \(\text{H}_2\text{O}_2\) decomposition into water and oxygen. The behavior can be attributed to the higher ability of the 400-series catalysts to catalyze the decomposition of \(\text{HO}_2\) radicals into O\(_2\) and H\(^+\), as has been reported to proceed by Fe\(^{3+}\) [12,42], wasting thus the valuable oxidant.

**Fig. 4: First-order kinetics of the degradation of phenol over selected catalytic systems with and without irradiation: \([\text{phenol}]_0=200 \text{ ppm}, T=40^\circ\text{C}, 20 \text{ mL } 3\% \text{H}_2\text{O}_2/h.**
3.3. Leaching of catalyst components into solution

In addition to the efficiency of the catalyst in degrading phenol and formed intermediates, it is also important to check whether the catalyst components do leach under reaction conditions into solution in form of ions because these ions can in turn be themselves toxic. The most active catalyst found in this work (CuFe$_{1.2}$O$_{2.8}$-550 under irradiation) was tested with this respect and the concentration of Cu$^{2+}$ and Fe$^{3+}$ ions that possibly leach in water during the reaction was determined by means of Atomic Absorption Spectroscopy. The results are summarized in Table 2.

![Fig. 5: The effect of thermal treatment temperature on the degradation of phenol over CuFe$_{1.2}$O$_{2.8}$: [phenol]$_o$=200 ppm, T=40°C, 20 mL 3%H$_2$O$_2$/h.](image)

| time (min) | [Fe$^{3+}$] (ppm) | [Cu$^{2+}$] (ppm) |
|------------|-------------------|-------------------|
| 150        | 0.49              | 0.83              |
| 180        | 0.80              | 2.51              |
| overnight  | 1.60              | 4.53              |

Table 2: The concentration of Cu$^{2+}$ and Fe$^{3+}$ ions leaching into solution during the degradation of phenol over CuFe$_{1.2}$O$_{2.8}$-550 under irradiation: [phenol]$_o$=200 ppm, T=40°C, 20 mL 3%H$_2$O$_2$/h.
Taking into consideration that only 90 min are needed to achieve more than 98% degradation of phenol, the results of the Cu²⁺ concentrations leaching into solution presented in Table 2 suggest the safe application of the above catalyst as it satisfies the WHO safety guidelines for copper in drinking water (2 mg/L) [43]. Moreover, the concentration of leached iron from CuFe₁₂O₂₈ after three hours of reaction (0.80 ppm) is below the limit established by The Illinois Environmental Protection Agency (IEPA) for iron in drinking water at 1.0 mg/l [44]. The low concentrations of leached Fe³⁺ and Cu²⁺ ions into solution, responsible for the homogeneously mediated decomposition, confirm the heterogeneity of the catalytic process where the decomposition of H₂O₂ takes place at the solid surface.

4. Conclusions:

In our attempts to develop a solid catalyst to degrade organic pollutants in wastewater via the Fenton-like reaction, six Fe-containing mixed oxide systems were prepared by the sol-gel auto-combustion method to have the following stoichiometries: CuFe₁₂O₂₈, BaFe₇.₂O₁₁.₈, BaFe₇.₂Cu₆.₈O₁₉.₆, BaFe₄.₈Cu₂.₈V₃.₀₂O₁₆.₆, BaFe₄.₈Cu₂.₈V₃.₀₂O₁₇.₇ and Ag₂Fe₅.₄V₃.₀₂O₁₆.₆. The prepared systems were thermally treated at 550°C, 650°C, 800°C and 1100°C, and then characterized by XRD to identify the present phases. The systems were tested with respect to their catalytic efficiency in the degradation of phenol (200 ppm) in water where CuFe₁₂O₂₈ was found to be the most reactive one (80% removal in 60 min). The rate of phenol degradation was enhanced under irradiation with a 30-W LED light source. The positive role of irradiation was most obvious in the case of Ag₂Fe₅.₄V₃.₀₂O₁₆.₆ in which almost complete conversion was achieved in 120 min compared to only 45% in the same period but without irradiation. The phenol degradation was found to obey first-order kinetics and it is believed that the first step of degradation process is that in which hydroxyl radicals are produced from H₂O₂. Analysis of the kinetic data suggests that the role of irradiation lies in increasing the rate of production of hydroxyl radicals.

The Fenton-like degradation of phenol using CuFe₁₂O₂₈ or Ag₂Fe₅.₄V₃.₀₂O₁₆.₆ as a catalyst seems to represent an effective method of degradation due to the high activity of these catalysts and due also to the fact that leaching of constituting ions of these catalysts into water is within the acceptable health safety range.

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References

[1] Murray C A and Parsons S A 2004 Chemosphere 54 1017
[2] Zelmanov G and Semiat R 2008 Water Res. 42 3848
[3] De Laat J, Le T G and Legube B 2004 Chemosphere 55 715
[4] De Laat J and T. G. Le T G 2005 Environ. Sci. Technol. 39 (2005) 1811
[5] Ensing B, Buda F and Baerends E J 2003 J. Phys. Chem. A 5731
[6] Neyens E and Baeyens J 2003 J. Hazard. Mater. 98 33
[7] Pignatello J J 1992 Environ. Sci. Technol. 26 944
[8] Yuan S H, Gou N, Alshawabkeh A N and Gu A Z 2013 Chemosphere 93 2796
[9] Wang N, Zheng T, Zhang G and Wang P 2016 J. Environ. Chem. Eng. 4 762
[10] Pliego G, Zazo J A, Garcia-Munoz P, Munoz M, Casas J A and Rodriguez J J 2015 Crit. Rev. Env. Sci. Technol. 45 2611
[11] Garrido-Ramírez E G, Theng B K G and Mora M L 2010 Applied Clay Science 47 182
[12] Casbeer E, Sharma V K and Li X-Zh 2012 Sep. Purif. Technol. 87 1
[13] Matavos-Aramyan S and Moussavi M 2017 Int. J. Environ. Sci. Nat. Res. 2 1D 55594
[14] Xu L and Wang J 2011 J. Hazard. Mater. 186 256
[15] Hansson H, Kaczala F, Marques M and Hogland W 2012, Int. J. Photoenergy Article ID 531076
[16] Ruales-Lonfat C, Barona J F, Sienkiewicz A, Bensimon M, Vélez-Colmenares J, Benítez N and Pulgarín C 2015 Appl. Catal. B Environ. 166-167 497
[17] Pastrana-Martínez L M, Pereira N, Lima R, Faria J L, Gomes H T and Silva A M T 2015 Chem. Eng. J. 261 45
[18] Kurian M and Babu R 2013 J. Environ. Chem. Eng. 1 86
[19] Du J, Bao J, Fu X, Lu C, Kim C H 2016 Appl. Catal. B: Environ. 184 132
[20] Wang J, Yao Zh, Wang Y, Xia Q, Chu H and Jiang Zh 2017 Environ. Pollut. in press.
[21] Wang N, Zhaob Q and Zhang A 2017 RSC Adv. 7 27619
[22] Khatri C and Rani A 2008 Fuel 87 2886
[23] Costa R C C, Leis M dF F, Oliveira L C A, Fabris J D, Ardisson J D, Rios R R V A, Silva C N and Lago R M 2003 Catal. Commun. 4 525
[24] Soliman Selim M, Turky G, Shouman M A and El-Shobaky G A 1999 Solid State Ionics 120 173
[25] Dom R, Subasri R, Radha K and Borse P H 2011 Solid State Commun. 151 470
[26] Wulfsberg G 2002 Inorganic Chemistry (University Science Books)
[27] Sun S, Yang X, Zhang Y, Zhang F, Ding J, Bao J and Gao Ch 2012 Prog. Nat. Sci.-Mater. 22 639
[28] Baldrian P, Merhautová V, Gabriel J, Nerud F, Stopka P, Hrubý M and Benes M J 2006 Appl. Catal. B: Environ. 66 258
[29] Qi Y, Liu Zh, Lu Ch and Zhang T 2017 Sci. Adv. Mater. 9 501
[30] Estrella M, Barrio L, Zhou G, Wang X, Wang Q, Wen W, Flanson J C, Irenkel A I and Rodriguez J A 2009 J. Phys. Chem. 113 1441
[31] Monova E, Tsonchera T, Ponerec D, Popora M, Velinor N, Kuner B, Tencher K and Mihor I 2011 Solid State Chem. 184 1153
[32] Hamdan N, Abu Haija M, Banat F and Eskhan A 2017 Desalin. Water Treat. 69 268
[33] Tan X, Li G, Zhao Y and Hu C 2009 Mater. Res. Bull. 44 2160
[34] Zhenchenko T A and Morozov V N 1995 Protein Sci. 4 251
[35] Kremer M L 1962 J. Catal. 1 351
[36] A. de Luis, J. I. Lombrana, F. Varona, and A. Menendez, Korean J. Chem. Eng. 26 (2009) 48
[37] Magaireh N, Master thesis, Yarmouk University 2013
[38] Babuponnusami A and Muthukumar K 2012 Chem. Eng. J. 183 1
[39] de Luis A, Lombrana J I, Varona F and Menendez A 2009 Korean J. Chem. Eng. 26 48
[40] Dumitrescu A M, Samoila P M, Nica V, Iordan A R and Palamaru M N 2012 Rev. Roum. Chim. 57 843
[41] Gogate M R, Spivey J J and Zoeller J R 1997 Catal. Today 36 243
[42] Babuponnusami A and Muthukumar K 2014 J. Environ. Chem. Eng. 2 557
[43] Fitzgerald D J 1998 Am. J. Clin. Nutr. 67 1098S
[44] http://www.idph.state.il.us