Degradation of paracetamol by advance oxidation processes using modified reticulated vitreous carbon electrodes with TiO$_2$ and CuO/TiO$_2$/Al$_2$O$_3$

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**HIGHLIGHTS**

- Photochemical, electrochemical and photoelectrochemical degradation of paracetamol.
- Low cost modified reticulated vitreous carbon electrodes coated with TiO$_2$.
- 95% Paracetamol degradation at 68% current efficiency was achieved.
- Performance parameters are comparable with more expensive electrodes.

**GRAPHICAL ABSTRACT**

Electrochemical cell used for the degradation of paracetamol in the presence of hydrogen peroxide using photochemical, electrolysis and photoelectrolysis processes with modified reticulated vitreous carbon (RVC) electrodes with TiO$_2$. The degradations followed a pseudo first order reaction kinetics with high percentage of TOC removal (80–99%), current efficiencies of 32–68% and energy consumption of 3.3–11.0 kW h L$^{-1}$.

**ABSTRACT**

The degradation of paracetamol in aqueous solutions in the presence of hydrogen peroxide was carried out by photochemistry, electrolysis and photoelectrolysis using modified 100 pores per inch reticulated vitreous carbon electrodes. The electrodes were coated with catalysts such as TiO$_2$ and CuO/TiO$_2$/Al$_2$O$_3$ by electrophoresis followed by heat treatment. The results of the electrolysis with bare reticulated vitreous carbon electrodes show that 90% paracetamol degradation occurs in 4 h at 1.3 V vs. SCE, forming intermediates such as benzoquinone and carboxylic acids followed by their complete mineralisation. When the electrolysis was carried out with the modified electrodes such as TiO$_2$/RVC, 90% degradation was achieved in 2 h while with CuO/TiO$_2$/Al$_2$O$_3$/RVC, 98% degradation took only 1 h. The degradation was also carried out in the presence of UV reaching 95% degradation with TiO$_2$/RVC/UV and 99% with CuO/TiO$_2$/Al$_2$O$_3$/RVC/UV in 1 h. The reactions were followed by spectroscopy UV–Vis, HPLC and total organic carbon analysis. These studies show that the degradation of paracetamol follows a pseudo-first order reaction kinetics.

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**1. Introduction**

The electrochemical Advanced Oxidation Processes (AOPs) degrade pollutants contained in water effectively and rely on highly oxidant species such as the hydroxyl radical HO$^-$ which has an
oxidation potential of +2.8 V vs. SHE (Huang et al., 1993; Jüttner et al., 2000; Brillas et al., 2009; Panizza and Cerisola, 2009; Siré and Brillas, 2012). This radical can be generated chemically, photochemically or electrochemically. If hydrogen peroxide is present in the same solution, the oxidation power would be even higher making the complete mineralisation of organic compounds faster and more effective being environmentally accepted (Wang et al., 2001).

The high oxidation powers of the AOPs has been used in a wide range of applications including: contaminated soil (Wang et al., 2001), sludge (Galindo et al., 2000), residual water (Scott and Ollis, 1995) and air (Xiao et al., 2002). In combination with other methods such as H2O2 and UV light, the efficiency of the oxidation depends on the concentration of hydrogen peroxide, the time of the photolysis and the frequency and wavelength of the incident light. The treatment of contaminated water containing pharmaceutical products in particular, the degradation of paracetamol, has been widely studied. Paracetamol has been found at concentrations up to 65 µg L\(^{-1}\) in waste waters and can be reduced to less than 10 µg L\(^{-1}\) after conventional waste water treatments (Roberts and Thomas, 2006). The environmental regulations in Mexico states that the effluents should comply with pH within 6–7, chemical oxygen demand (COD) of 100–120 mg L\(^{-1}\), biochemical oxygen demand (BOD) of 200–250 mg L\(^{-1}\), grease 20–30 mg L\(^{-1}\) and total suspended solids (TSS) 150–180 mg L\(^{-1}\) (INE, 1995), however, there are no specific regulation for the disposal of particular pharmaceutical compounds.

AOPs such as H\(_2\)O\(_2\)/UV, O\(_3\)-based processes and photo-Fenton have been used to degrade several pharmaceuticals such as: metronidazole (Shemer et al., 2006), carbamazepine (Vogna et al., 2004a), diclofenac (Ravina et al., 2002; Vogna et al., 2004b), naproxen (Pereira et al., 2007) and penicillin (Arslan-Alaton et al., 2004), amoxicillin (Andreonzi et al., 2005), carbamazepine (Ikehata et al., 2006), sulphamidon (Huber et al., 2005), penicillium (Arslan-Alaton and Dogrul, 2004), metromidazol (Shemer et al., 2006) and paracetamol (Sirés et al., 2006; Waterston et al., 2006; Klavarioti et al., 2009). In these studies the degradation can be between 30% up to 98% (Adams et al., 2002; Vogna et al., 2004a).

Partial degradation of paracetamol is commonly reported in the literature, e.g., Vogna et al. (2002) reported that using H\(_2\)O\(_2\)/UV, they obtained 2-hidroxi-4-(4-N acetyl) aminophenol, acetamide and oxamic acids as intermediates, while Andreozzi et al. (2003) reported 30% and 40% degradation using O\(_3\) and H\(_2\)O\(_2\)/UV at pH 2.0 and 7.0, respectively. The oxidation with ozone produces hydrogen peroxide as well as intermediate species such as hydroquinone, 1,2,4-trihydroxibenzenze and 2-hidroxi-4-(N-acetyl) aminophenol and glycolixolic, oxalic and formic aliphatic acids (Andreonzi et al., 2003).

In a detailed study of the photocatalytic degradation of paracetamol using TiO\(_2\) in suspension, UV-light and H\(_2\)O\(_2\), (Yang et al., 2009) it was shown that the hydroxyl radical (•OH) caused the highest degradation of paracetamol compared with other species such as H\(_2\)O, O\(_2\) and H\(_2\)O\(_2\) and follows a second-order rate constant with paracetamol. The degradation of paracetamol on boron doped diamond (BDD) electrodes decreased the total organic carbon (TOC) by more than 98% (Brillas et al., 2005). BDD electrodes are the preferred anode material due to their ability to operate at high positive potentials with minimum degradation and high efficiency. However, they are still expensive and other cheaper more available methodologies have been investigated. Some of these include the electrolytic process using titanium anodes modified with TiO\(_2\) and with mixtures of RuO\(_2\)/IrO\(_2\) to degrade phenolic acid (Rajkumar and Palanivelu, 2004), clofibrac acid (Sirés et al., 2007) and piroxicam (Torriero et al., 2006).

The catalytic properties of low cost catalyst such as CuO supported on alumina, modified with a monolayer of TiO\(_2\), (CuO/TiO\(_2\)/Al\(_2\)O\(_3\)) have been studied for the cyclopropanation of styrene (Liu et al., 2003). Higher activity and selectivity has been obtained by supporting the CuO catalyst on TiO\(_2\)/Al\(_2\)O\(_3\) rather than on separated TiO\(_2\) or Al\(_2\)O\(_3\), indicating the relationship between the catalyst support and the activity. The authors suggested that the highly dispersed CuO and the monolayer of dispersed TiO\(_2\) interact with on Al\(_2\)O\(_3\) and propose that Cu(II) in the cupric oxide gets reduced during the cyclopropanation reaction (Fraile et al., 1997; Liu et al., 2003).

The objective of this work is to determine the degradation route of paracetamol in the presence of TiO\(_2\) and CuO/TiO\(_2\)/Al\(_2\)O\(_3\) modified electrodes supported on reticulated vitreous carbon (RVC) (Friedrich et al., 2004; Recio et al., 2011). The importance of these electrodes is their low cost and their potential to be employed in a scale-up water treatment process for large volumes containing organic waste material.

2. Experimental

Three different processes to degrade paracetamol were studied; each comprises several methodologies which are listed in Table 1 and described in the following sections.

2.1. Synthesis of TiO\(_2\) using titanium mesh

The TiO\(_2\) used to prepare the modified electrodes and in the photochemical process was prepared by dissolving a titanium mesh in concentrated HCl (36.5–38%, J.T. Baker) heated at 80 °C while stirring for ≈3 h in order to form TiCl\(_4\) (Esquivel et al., 2011). The solution was neutralised with ammonium hydroxide to form TiO\(_2\) followed by the addition of 10% HNO\(_3\) (J.T. Baker) to complete the oxidation of Ti\(^0\) to Ti\(^{4+}\), according to the following equations:

\[
\text{Ti}^0 + 6\text{HCl} + 2\text{H}_2\text{O} \rightarrow \text{TiCl}_4 + 2\text{HCl} + 2\text{H}_2\text{O}
\]

(1)

\[
\text{TiCl}_4 + 2\text{NH}_4\text{OH} \rightarrow \text{TiO}_2 + 2\text{HCl} + 2\text{NH}_4\text{Cl}
\]

(2)

The TiO\(_2\) formed was characterized by EDAX, SEM and X-ray diffraction.

2.2. Preparation of the RVC modified electrodes

Two 100 pores per inch (ppi) RVC electrodes of 1 × 3 × 0.05 cm dimensions were used as anode and cathode to prepare the modified electrodes by electrophoresis. The electrodes were glued to a graphite rod with carbon cement and were completely immersed in a solution of 0.5 M Na\(_2\)SO\(_4\) at pH 5 contained in a BAS cell of 50 cm\(^3\) capacity. The graphite rod was kept out of solution and the distance between the electrodes was 3 cm. One gram of each catalyst TiO\(_2\) and CuO/TiO\(_2\)/Al\(_2\)O\(_3\), prepared by the method Sol–Gel, was suspended in separated experiments in 20 cm\(^3\) of ethanol and deposited on the anode by applying 4 V across the RVC electrodes during 60 s via a Bioelec model FR500-125 power supply. After the electrodeposition, the anodes were submitted to a heat treatment process for 3.5 h at 550 °C in a furnace (Fisher-Scientific Isotemp) in nitrogen atmosphere. The deposits were characterised by a Scanning Electron Microscope (SEM) JEOL6060LV coupled with a microprobe OXSOR and with an Energy-Dispersive X-ray analysis (EDAX). The XRD analysis confirmed the presence of the photochemically-active phase anatase of TiO\(_2\).

2.3. Photochemical process I (photolysis and photocatalysis)

A cell with 0.150 dm\(^3\) capacity shown in Fig. 1 containing 96 mg L\(^{-1}\) of paracetamol and 0.01 M of H\(_2\)O\(_2\) in deionised water was used. The experiments lasted ≈6 h using TiO\(_2\) and CuO/TiO\(_2\)/
Al₂O₃ powders as catalysts while the solution was stirred with a magnetic follower. A mercury lamp with 350 nm maximum wavelength was used as a source of photons and the development of the solution was followed by taking aliquots of $1 \times 10^{-3}$ dm³ every 15 min.

2.4. Electrochemical process II (electrolysis and electrocatalysis)

The electrolyses were carried out in a typical three-electrode cell containing 96 mg L⁻¹ of paracetamol and 0.01 M of H₂O₂, with 0.5 M Na₂SO₄ as a supporting electrolyte. A 100 ppi bare RVC electrode and the two modified RVC electrodes were used as anodes while the cathode and reference electrodes were a platinised titanium mesh and a saturated calomel electrode (SCE), respectively. An electrode potential of 1.3 V vs. SCE was applied to the anodes based on earlier studies that show that at this potential the oxidation of paracetamol occurred preferentially on the electrodes used in this study. The modified working electrodes were TiO₂/RVC and CuO/TiO₂/Al₂O₃/RVC prepared as explained in Section 2.2. The development of the reaction was followed by analysing $1 \times 10^{-3}$ dm³ aliquots of the electrolyte every 15 min during 6 h. A Princeton Applied Research bi-potentiostat Model 366 was used for the electrochemical measurements.

2.5. Photoelectrochemical process III

Similar electrochemical cell system with the modified electrodes as described in the previous section was used. In addition, the system was irradiated with UV light from an Hg lamp at 350 nm wavelength maintaining the potential of the working electrode at 1.3 V vs. SCE (Fig. 1). The reaction was carried out over 60 min and the degradation of paracetamol was followed by taking aliquots of $1 \times 10^{-3}$ dm³ every 10 min.

2.6. Analytical methods

The reaction intermediates were analysed using an HPLC CC5, Solvent Deliver System PM80, fitted with UV–Vis detector 116A and temperature control LC-22C. The mobile phase was a 30/70% (v/v) mixture of methanol/phosphate buffer adjusted to pH 2.6 at 0.8 $\times 10^{-3}$ dm³ min⁻¹ flow rate. The concentration of the phosphate buffer was 1 $\times 10^{-2}$ M and the column was an Alltima HPC18 of 5 μ with 4.6 mm ID and 150 mm length. The retention times of the carboxylic acids intermediates such as oxalic (2.18 min) and oxamic acid (2.6 min) as well as those of hydroquinone (2.6 min), benzoquinone (3.7 min) and paracetamol (3.2 min) were compared with standards purchased from Merck. The intermediates were chosen based on the literature reports of the degradation of paracetamol. Typically, 20 μL of a solution containing one standard at the time was injected into the chromatographic column. The concentration of the standards varied between 12.00 and 15.00 mg L⁻¹. Before injecting the samples from the oxidation process into the HPLC, the samples were analysed by an UV–Vis spectrophotometer Cary 50 Probe to confirm the presence or the absence of organic compounds. The total organic carbon (TOC) was determined at 680 °C with a TOC analyser SHIMADZU. An acid digestion method was used to prepare the samples before the TOC analysis.

3. Results and discussion

3.1. Photochemical process I (photolysis and photocatalysis)

Fig. 2 shows the concentration decay of 96 mg L⁻¹ of paracetamol, determined by HPLC, vs. time for the photochemical process
I comprising three different methods (see Table 1). Curve (1) represents the paracetamol degradation during the photolysis process using only UV light (method 1) and shows that the concentration decreased 82% down to 76.8 mg L\(^{-1}\) after 6 h. In the presence of TiO\(_2\)/UV (method 2) represented by curve (2), the degradation reached 80% down to 19.2 mg L\(^{-1}\) after 6 h. When CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV was used (method 3) curve (3), the concentration after 6 h was 38.6 mg L\(^{-1}\), indicating 60% degradation. The degradation of paracetamol in these systems follows the order: TiO\(_2\)/UV > CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV > UV. The catalytic activity of the p-type semiconductor TiO\(_2\) is higher due to its intrinsic ability to generate electron–holes pairs under UV radiation. The adsorption of photons creates an electronic distribution on the TiO\(_2\) surface that favours the formation of free radicals (Lai et al., 2006; Peralta-Hernández et al., 2007).

In the case of CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV, the presence of a semiconductor n-type such as CuO is considered as an impurity and a synergistic effect between TiO\(_2\) and CuO is assumed, causing an increase in the band gap and therefore more resistance to the electron transfer. This is the reason why in the method represented by the curve (3), the degradation process is not effective.

### 3.2. Kinetic study

The inset in Fig. 2b shows the logarithm of the normalised concentration of paracetamol \(c_t/c_0\) as a function of time for methods 1, 2 and 3. If the degradation of paracetamol follows a pseudo-first order kinetics reaction the concentration decay can be expressed in terms of the apparent rate constant, \(k_{\text{app}}\). The figure shows that the data for the three systems: UV, TiO\(_2\)/UV and CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV (see Section 3.1) are linear with an apparent rate constant of \(4.0 \times 10^{-3}\), \(1.5 \times 10^{-3}\) and \(1.2 \times 10^{-3}\) s\(^{-1}\), respectively indicating a pseudo-first order kinetic reaction. The experiment with TiO\(_2\)/UV shows higher percentage of degradation than when the experiment was carried out with UV and CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV. Fig. 3 shows the chromatograms of the solution at the beginning (solid line) and after 360 min (dash line) of the degradation process as well as the standards of paracetamol, carboxylic acids and hydroquinone, found as intermediates. The curve after 360 min reaction shows that the amount of paracetamol concentration decreased 80%. The curves (solid line) and (dash line) show the signal of the paracetamol at an elution time of 3.2 min and two additional signals, at 2.1–2.3 and 2.6–2.7 min corresponding to the carboxylic acids and hydroquinone, respectively. The degradation of paracetamol occurs via the formation of oxalic and oxamic carboxylic acids therefore a standard of oxalic acid was used to follow the formation of by-products. The presence of these intermediates was confirmed by UV–Vis spectroscopy.

### 3.3. Electrochemical process II (electrolysis and electrocatalysis)

Fig. 4 shows the normalised concentration change of paracetamol as a function of time with the three electrochemical systems (methods 4, 5 and 6). The solution contained 96 mg L\(^{-1}\) of paracetamol and 0.5 M Na\(_2\)SO\(_4\) at pH 5 and the electrode potential was held at 1.3 V vs. SCE. The electrolysis using RVC (curve 1) shows 90% degradation in 4 h while the electrolysis with the modified electrode TiO\(_2\)/RVC (curve 2) shows 90% in 2 h reaction. When CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC was used (curve 3), 98% degradation was achieved in only 1 h. These reactions follow a pseudo-first order kinetic behaviour as the inset in the figure shows. The apparent rate constants \(k_{\text{app}}\) for these systems are \(4.3 \times 10^{-2}\), \(16.6 \times 10^{-3}\) and \(18.1 \times 10^{-3}\) s\(^{-1}\) for the systems: RVC, TiO\(_2\)/RVC and CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC, respectively.

### 3.4. Photoelectrochemical process III

Fig. 5 shows the normalised concentration decay of paracetamol when the initial concentration was 96 mg L\(^{-1}\) in 0.5 M Na\(_2\)SO\(_4\) at pH 5. After 1 h reaction with TiO\(_2\)/RVC/UV (method 7) (curve 1) at 1.3 V vs. SCE the concentration decreased to 4.8 mg L\(^{-1}\), representing 95% degradation. When CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC/UV (method 8) was used the concentration decay of paracetamol (curve 2) was 0.96 mg L\(^{-1}\) (99% degradation) after less than 1 h reaction.
The kinetic rate constants calculated from the slopes of the curves shown in the inset of the figure of the systems described above were \( 13.8 \times 10^{-3} \, \text{s} \) (curve 1) and \( 15.1 \times 10^{-3} \, \text{s}^{-1} \) (curve 2).

### 3.5. Percentages of paracetamol decay

Table 1 shows the concentration of different intermediates species found in solution after 1 and 2 h degradation of 96 mg L\(^{-1}\) of paracetamol for the different systems described above. In the UV system the concentration of paracetamol only decreased 2% and 4% during the 1st and 2nd h, respectively without any detectable concentration of intermediates. When the degradation was carried out using the photocatalytic system, TiO\(_2\)/UV (method 2) small amounts of oxalic acid and benzoquinone were detected at very poor percentages of degradation. Similarly, very low concentrations of intermediates were detected when the system CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV (method 3) was used. The electrolysis with RVC (method 4) produced larger amounts of carboxylic acids and benzoquinone with a degradation of 80% of paracetamol in 2 h. However, the electrolysis with the modified electrode TiO\(_2\)/RVC (method 5) 90% degradation without formation of intermediates was achieved also in 2 h. When the modified electrode CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC (method 6) was used, the degradation reached 98% without intermediates in 1 h. The other systems tested were: incident UV light on TiO\(_2\)/CVR/UV (method 7) which achieved 95% degradation in 1 h, while the system CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC/UV (method 8) showed 99% in the same period of time, indicating that the use of UV significantly increases the oxidation rate.

### 3.6. Determination of the total organic carbon (TOC) during degradation of paracetamol

Fig. 6 shows the development of the total organic carbon (TOC) values during the degradation of paracetamol over 1 h reaction of the photochemical processes I, II and III for all methods employed except method 1, listed in Table 1. Curves (2) and (3) correspond to the experiments carried out with powdery catalyst in a stirred solution; TiO\(_2\)/UV (method 2) and CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/UV (method 3). Curves (7) and (8) represent the development of TOC when a photoelectrochemical process was carried out with the modified RVC electrodes and with UV incident light, method 7 (TiO\(_2\)/RVC/UV) and method 8 (CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC/UV) listed in Table 1. The photochemical processes (curves 2 and 3) show that the TOC values decrease to 30 and 60 mg dm\(^{-3}\), respectively after 1 h confirming that there is still organic matter in solution. In the case of the photoelectrochemical processes (curves 7 and 8) the depletion of the TOC is significantly more important, 90 and 100 mg dm\(^{-3}\), respectively. This demonstrates the complete demineralisation of the drug after 1 h reaction using process III.

The Fig. 6 also shows that in the electrochemical processes II in the absence of UV light, the values of TOC during the electrolysis with an RVC electrode (curve 4) are still high after 1 h, indicating poor mineralisation. The curves (5) and (6) represent the development of the TOC values during the electrolysis with the modified electrodes TiO\(_2\)/RVC and CuO/TiO\(_2\)/Al\(_2\)O\(_3\)/RVC, respectively. The TOC decreases considerably, especially for the system containing CuO and indicates that the system represented by curve (6) is the most efficient system to degrade paracetamol.

### 3.7. Current efficiency for the mineralisation process

In this study the systems that yielded the highest percentage of mineralisation of paracetamol were considered to calculate the current efficiency and the energy consumption. These include the electrochemical and photoelectrochemical processes II and III respectively which comprise the methods number 5, 6, 7 and 8. Less efficient methods such as 1, 2, 3 and 4 present higher energy consumption due to their lower percentage of TOC and were not calculated as they are not attractive to scale-up the process. The global mineralisation of paracetamol oxidation can be written as (Brillas et al., 2005):

\[
\text{HOC}_6\text{H}_4 \cdot \text{NHCOCH}_3 + 14\text{H}_2\text{O} \rightarrow 8\text{CO}_2 + \text{NH}_4^+ + 33\text{H}^+ + 34\text{e}^- \quad \text{(3)}
\]

The current efficiency at time t can be calculated by the following equation (Brillas et al., 2005):

\[
\text{Current efficiency} = \varphi = \frac{\Delta(\text{TOC})_{\text{exp}}}{\Delta(\text{TOC})_{\text{theory}}} \times 100 \quad \text{(4)}
\]

where \(\Delta(\text{TOC})_{\text{exp}}\) and \(\Delta(\text{TOC})_{\text{theory}}\) are the experimental values of TOC at time t and the theoretical calculation of TOC assuming that Eq. (3) is the only one occurring during the electrolysis process.
The changes of TOC, current efficiency and energy consumption are shown in Table 1 for those methods that offered the highest removal percentage of TOC. The modified electrodes, arranged from those reported by (Brillas et al., 2005) who achieved between 3.3 and 11.0 kW h m⁻³ while for the degradation of 15 mg L⁻¹ β-blockers was higher (36 kW h m⁻³) (Sirés et al., 2010). The comparison with the recovery of heavy metals shows that the values in this paper are within the same order of magnitude: 500 mg L⁻¹ of Pd(II) (1.04–2.8 kW h m⁻³) (Terrazas-Rodríguez et al., 2011b), 922 mg L⁻¹ of Cu(II) (4–7 kW h m⁻³) (Rivera et al., 2008), 1187 mg L⁻¹ of Sn(IV) (2–10 kW h m⁻³) (García-Gabaldón et al., 2005) and 55 mg L⁻¹ of Cd(II) (1.25–2.5 kW h m⁻³) (Grau and Bisang, 2001) in divided and undivided rotating cylinder electrodes (RCEs).

4. Conclusions

Using a photochemical degradation process, the effective mineralisation of paracetamol in different systems occurs in the following order during 6 h period: TiO₂/UV > CuO/TiO₂/Al₂O₃/UV > UV. When an electrocatalysis process was used the degradation of paracetamol can be achieved quicker after 1 and 2 h of reaction with up to 90% and 98% degradation, respectively with the modified electrodes: CuO/TiO₂/Al₂O₃/RVC > TiO₂/RVC > RVC. The photoelectrocatalytic process also degrades paracetamol up to 95% and 99%, and the TOC removal indicates complete mineralisation in 60 min in the following order: CuO/TiO₂/Al₂O₃/RVC/UV > TiO₂/RVC/UV.

The electrolysis with reticulated vitreous carbon shows the presence of intermediates such as carboxylic acids, hydroquinone and benzoquinone in considerable amounts resulting in a poor percentage of degradations which was confirmed by the values of TOC.

The kinetic study shows that in all cases the degradation of paracetamol follows a pseudo-first order reaction. The CuO/TiO₂/Al₂O₃/RVC/UV system shows the largest pseudo kinetic constant indicating rapid conversion of paracetamol directly to CO₂.

The system with the highest degradation efficiency was the photoelectrocatalysis (method 7) using TiO₂/RVC/UV modified electrode which shows 95% degradation at 68% current efficiency. The efficiency values are in the same order of magnitude as those...
reported in the literature for paracetamol while the energy consumption compares with that reported for heavy metal recovery in different electrochemical reactors.

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