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Pharmaceutically Active Compounds in Wastewater Treatment Plants: Electrochemical Advanced Oxidation as Onsite Treatment

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6.1 Introduction

6.1.1 Emerging Organic Contaminants

Emerging organic contaminants (EOCs) or contaminants of emerging concern can be defined as naturally occurring, manufactured, or manmade chemicals or materials whose associated risks cannot be properly evaluated due to the lack of data about their environmental fate and ecotoxicological or toxicological effects [1, 2]. A contaminant remains "emerging" as long as there is a scarcity of information in the scientific literature about the associated potential risks it could cause [1, 2].

EOCs broadly include "lifestyle compounds," personal care compounds, pharmaceuticals including hormones, and plasticizers [3]. Pharmaceutical products account for 70% of the approximately 4500 chemical compounds available in the world, and the production of pharmaceutical compounds and other medicines is still increasing [4]. Over the years, population growth and the development of new medicines to prevent or cure diseases with unknown fates and effects on the environment has made these compounds deserve special attention [5].

Over the last few decades, the subject of EOCs has become a worldwide issue of increasing environmental concern, and intensive research has been carried out on a range of different topics such as their occurrence and fate in the environment as well as treatment methods. A total of 117 papers were published in 2013 (Figure 6.1), and the number of studies has continued to increase since then to 330 in 2019 (almost two times more than five years before).

6.1.2 Occurrence and Fate of EOCs

One of the primary current worldwide concerns is the growth of pollution due to EOCs arising from many urban, industrial, and agricultural activities. Technological

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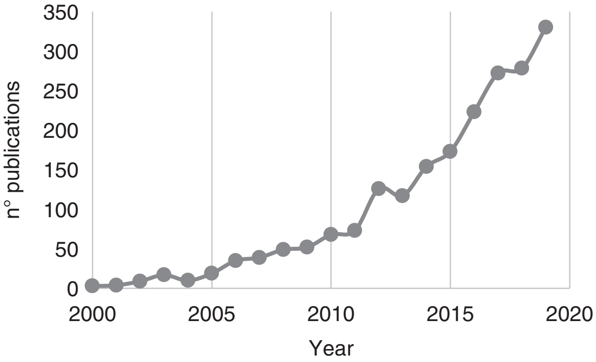

Figure 6.1 Number of publications on emerging organic contaminants from 2000 to 2019.

advances in analytical instrumentation and techniques have enabled researchers to detect and quantify EOCs in different environmental compartments (soil, air, and water) [6–8].

EOCs are now commonly detected in the environment due to their constant introduction through the disposal of wastewater, biosolids, and manure (Figure 6.2). Waste streams from hospitals, wastewater treatment plants (WWTPs), and sewage treatment plants have been identified as significant contributors to environmental contamination with EOCs [3, 9–11]. Besides the ubiquitous occurrences of EOCs in the environment, significant and measurable concentrations of ibuprofen, diclofenac, and carbamazepine were also found in drinking waters, e.g. [12, 13]. Surface water, groundwater, and soils are interrelated, and upon arrival in the environment, EOCs can undergo significant transformation including (bio)degradation, sorption at the sediment, and transport in the aqueous phase. This transformation depends on EOC physicochemical properties such as volatility, polarity, adsorption properties, persistence, and the properties of the interacting compartments: for example, the presence of a community of organisms that can transform the contaminants through metabolic networks and the bioavailability of contaminants, especially in sediments and soil [14, 15]. Generally, compounds with octanol/water partition coefficient (Log K_{ow}) lower than 3.0 are not expected to be adsorbed significantly to the particles, but compounds with relatively high Log K_{ow} values and pKa values below the pH of the wastewater are expected to be dissociated in the aqueous phase and not bound to the particles. Despite known chemical properties, it is difficult to predict their behavior in the environment as it depends on several variables [16].

In addition to direct sources of EOCs in the environment, other potential routes for these compounds may be considered. For example, reusing treated wastewater for irrigation in agriculture can also represent a risk to human health as EOCs might transfer to soil, potentially increasing the risk of consumption as they are not regulated and can be accumulated within crop plants. This fact has been already reported by several studies [15–20]. Malchi et al. [21] found 14 different EOCs, such as carbamazepine, caffeine, clofibric acid, diclofenac, ibuprofen, ketoprofen,

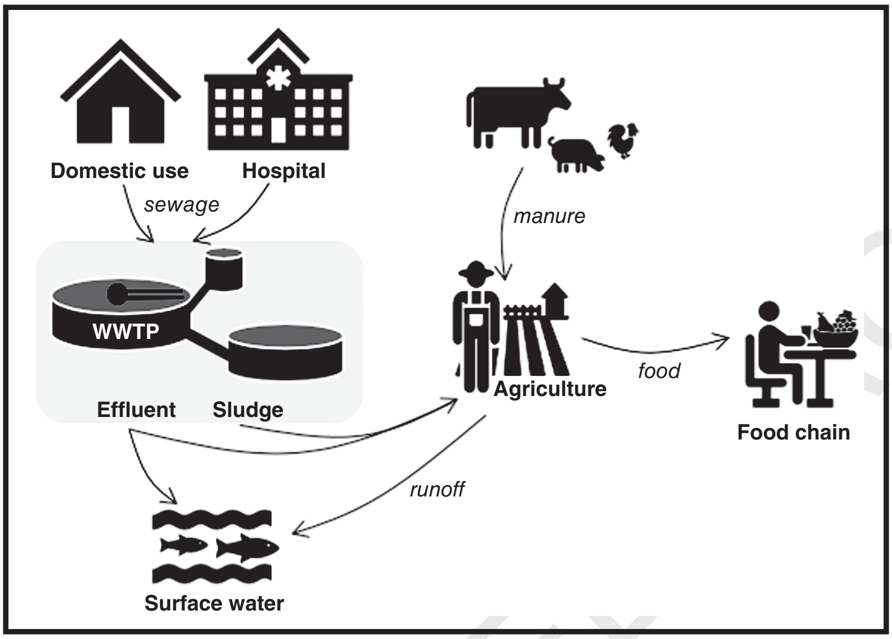

Figure 6.2 Origins of EOCs ~~such as pharmaceuticals~~ and routes into the environment.

and naproxen in carrots and sweet potatoes irrigated with treated wastewater. It is difficult to predict what environmental and public health implications may arise from the occurrence of these chemicals in the environment since EOCs are usually found in the environment at trace concentrations (i.e., between $\text{ng}\,\text{l}^{-1}$ and $\mu\text{g}\,\text{l}^{-1}$ or even lower). However, concerns are increasing about antimicrobial resistance [22] and chronic impacts on biodiversity, including endocrine-disrupting effects on fish [23–25]. Other effects/consequences of EOCs can be found summarized in the literature [10].

6.1.2.1 EOCs in WWTPs

Over the last two decades, the occurrence of several EOCs in the influents and treated effluents of WWTPs has been documented worldwide [3, 5, 11, 26]. In general, conventional WWTPs use a combination of primary (physical) and secondary (biological) methods. They were primarily designed to remove pathogens, suspended solids, and gross organic and inorganic matter, rather than remove the increasing numbers of new chemicals. Worldwide water scarcity is increasing the demand for non-conventional water resources. Nowadays, WWTPs have shown fairly limited effectiveness in EOC removal; there may still be significant concentrations of EOCs in effluents discharged into surface water bodies [27–29].

A combination of regulations and management measures with respect to discharging EOCs into the environment, as well as their occurrence in the environment, is fundamental to achieving efficient water resource management. Although there are no legal discharge limits for EOCs, some regulations have been published in the last few years. Actions have been initiated across Europe, but Switzerland is currently the only country regulating pharmaceuticals and micropollutants in wastewater. Switzerland also aims to remove a total of 50% of micropollutants by upgrading one-seventh of all wastewater plants to use activated carbon and ozonation by 2040, as part of the Swiss micropollutants action plan ([30] and references therein).

Environmental quality standards for a minority of chemicals such as nonylphenol and bisphenol A have been stipulated in Directive 2008/105/EC. Nonylphenol and nonylphenol ethoxylates have also been recognized as toxic substances by the Canadian government [31]. Other EOCs, such as pharmaceutical and personal care products and steroid hormones, are not included in the list of regulated substances yet. To set regulatory limits, further research on biological responses to these compounds is needed [31].

Recent investigations have examined the fate of EOCs during wastewater treatment, focusing on their removal during conventional (e.g. activated sludge) and advanced (e.g. ozonation and membrane filtration) treatment processes. The results suggest that more studies in EOC remediation should fill the knowledge gaps [10]. The water industry will most likely undergo several changes in the coming years due to rapid urbanization, severe climate change, rising customer demand, and the implementation of emerging digital technologies.

6.1.3 Water Challenges

Water is an essential resource for sustaining humanity and life in general. Access to water, sanitation, and hygiene is a human right; however, half the world's population experiences severe water scarcity at least one month a year [32]. Although approximately 70% of the Earth's surface is covered with water, only a small fraction (2.5%) is freshwater compatible with terrestrial life. Nowadays, intensive pollution issues and, consequently, lack of water quality in many areas in the world have raised awareness about the importance of water. According to the European Environmental Agency Report, only around 40% of surface waters (rivers, lakes, and transitional and coastal waters) have a good ecological status or potential, and 38% have a good chemical status [33]. Nevertheless, effective strategies for addressing water contamination are latent in the modification and research of technologies aiming at wastewater treatment and integrating them into a holistic, circular water management system.

In this sense, various directives and protocols related to better water quality and management have been adopted in the last two decades. In 2000, the European Union (EU) introduced a list of 33 priority substances to control the chemical quality of water (Water Framework Directive, 2000/60/EC) [34], which was later updated to 45 substances in 2013 (Directive 2013/39/EU) [35].

According to the UN, the world population is expected to reach more than 9 billion people in 2050, and a continuous increase in water demand is observed as a consequence. The volume of wastewater generated by domestic, industrial, and commercial sources has been increasing along with population, urbanization, improved living conditions, and economic development [36]. At present, about 1 billion cubic meters of treated urban wastewater are reused annually, accounting for approximately 2.4% of treated urban wastewater effluents and less than 0.5% of annual EU freshwater withdrawals. To make sure there is enough food for the growing population, it is estimated that global food production needs to increase by 70%; agriculture plays a key role and is a huge responsibility of water management, as it uses 70% of the available freshwater [37]. Thus, agricultural water consumption is also expected to grow by about 20% globally by 2050 [38]. In May 2018, the European Commission proposed new rules to stimulate and facilitate water reuse in the EU for agricultural irrigation [32]. The Regulation proposed by the Commission aims to alleviate water scarcity across the EU, and it will ensure that treated wastewater intended for agricultural irrigation is safe, protecting citizens and the environment. The proposal is part of the Commission's 2018 Work Programme, following up on the Circular Economy Action Plan, and completes the existing EU legal framework on water and foodstuffs.

Wastewater contains a great number of valuable resources such as nitrogen, phosphorus, energy, and other nutrients that can be recovered and reused in a circular economy to protect scarce and threatened resources in addition to reducing water consumption. However, changing from a linear model to a more circular economy requires rethinking traditional wastewater treatment models and understanding the interlinkages between the different Sustainable and Development Goals (SDGs). Some possible interlinkages that can be drawn from the SDG6 are shown in Figure 6.3. The SDG6 consists of the development of cost-efficient technologies to remove contaminants from wastewater, ensuring availability and sustainable management of water and sanitation for all. The SDG6 is an important element of the SDG2, promoting sustainable agricultural practices, as it will contribute to safe water reuse. At the same time, the SDG6 is also linked to other parts of Agenda 2030, such as those related to poverty, nutrition, health, education, gender,

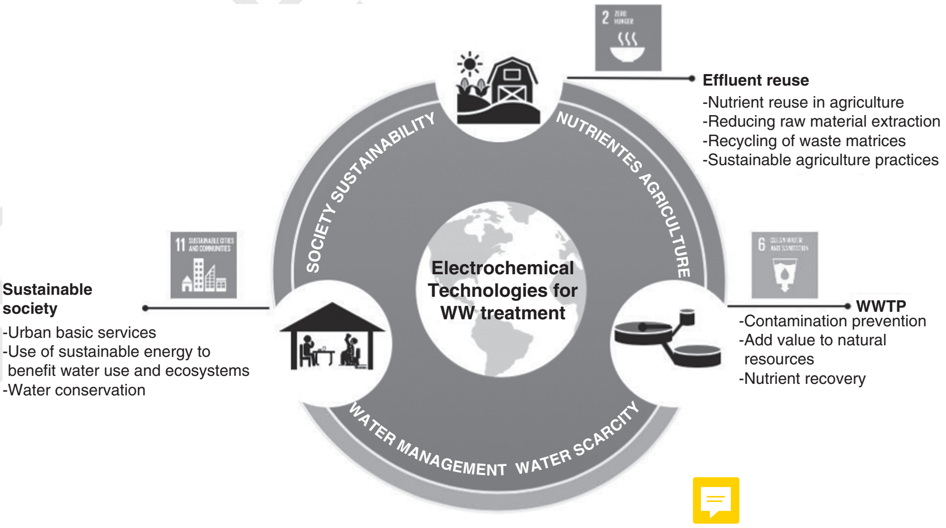

Figure 6.3 Interlink of Sustainable Development Goals addressing wastewater treatment challenges with ~~electro-based technologies,~~

economic growth, and climate change. Explicit links can be made between SDG6.2 and those relating to basic urban services, with the proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated by cities (SDG11). The relative importance of these interlinkages can vary based on regional or socio-economic context [39].

6.1.4 Technologies for Wastewater Treatment – Electrochemical Process

The treatment of urban wastewater is one of the biggest challenges of the twenty-first century~~, and the development of cheaper, effective, and novel methods of decontamination is currently an active field of research, as shown by the numerous publications appearing each year (Figure 6.4).~~

~~In recent decades, research efforts have been made to develop more effective technologies for the remediation of waters containing organic pollutants.~~ Several physicochemical techniques have been exploited, such as activated carbon adsorption, advanced oxidation processes (AOPs), nanofiltration, reverse osmosis, and membrane bioreactors, to achieve high levels of ~~contaminant~~ removal [40]. However, the application of such technologies implies a high cost for water treatment. In addition, these technologies in some cases do not achieve complete mineralization of the contaminant, sometimes leading to secondary pollution [41]. Successful mitigation strategies have not yet been established, and the search for alternative techniques is necessary to improve the degradation of organic contaminants (parent and secondary metabolites) and reduce the costs associated with effluent treatment in WWTPs, allowing its safe reuse [40, 42].

All the technologies have constraints not only in terms of cost but also in terms of feasibility, practicability, reliability, environmental impact, sludge production, operation difficulty, pretreatment requirements, and the formation of potentially toxic

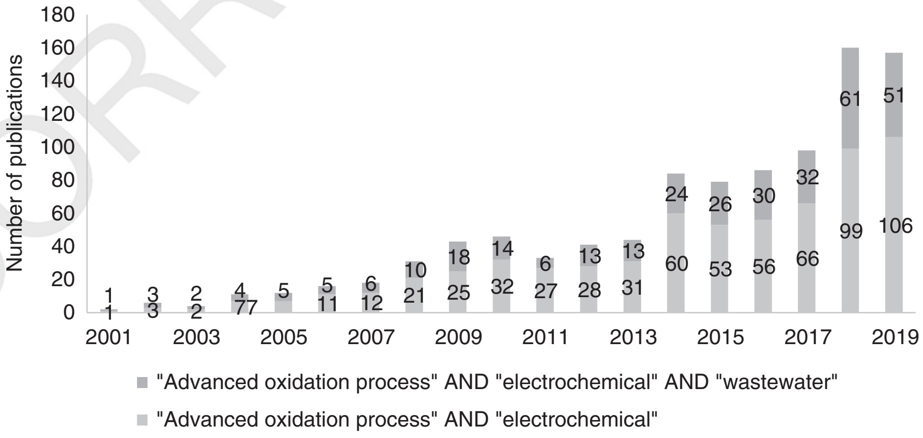

Figure 6.4 Number of publications from 2001 to 2019 on advanced oxidation processes with electrochemical technology and wastewater~~.~~

byproducts. Among the various treatment processes currently cited for wastewater treatment, only a few are commonly employed by the industrial sector for technological and economic reasons [43].

The use of chemically strong oxidation agents such as hydroxyl radicals, chlorine, hydrogen peroxide, ozone, and combinations of these oxidants has been investigated for chemical oxidation of EOCs from wastewater. AOPs constitute important, promising, efficient, and environmentally friendly methods developed to principally remove organic pollutants from waters and wastewaters. Based on the ways oxidation agents are produced, AOPs can be classified in different ways such as Fenton oxidation catalytic ozonation, photocatalytic oxidation, and electrochemical oxidation [44].

Among the various technologies, the so-called electrochemical AOPs have generated increasing interest; over the last two decades, electrochemical technology or electrochemical-AOPs have gained increasing attention as a promising class of AOPs, representing half the publications in this field (Figure 6.4).

Electrochemical (EK) technology is a high-efficiency technology for oxidizing and removing a broad range of recalcitrant organic pollutants such as dyes, pesticides, herbicides, pharmaceuticals, antibiotics, hormones, chelating agents, and microcystin toxins [44–47]. EK processes have been investigated for wastewater treatment and offer a great advantage over conventional treatments since no additional chemicals are required as e.g. in electro-Fenton oxidation, and the electron may be considered as a “green” controllable reagent that does not generate sludge [48]. The great effectiveness of electrochemical methods is due to the production of the hydroxyl radical ($^{\bullet}$OH), which is a non-selective, very powerful oxidizing agent (2.8 V) that reacts with organics, giving dehydrogenated or hydroxylated derivatives until complete mineralization is reached [49]. Compared to other AOPs, electrochemicals are more efficient; for example, in [50], the study showed chemical oxygen demand (COD) degradation efficiency of 38.1%, which is higher than that obtained using ozonation (17.0%). Additionally, the specific energy demand is lower for electrochemical AOPs (93.6 kWh/kg m COD) than for ozonation (125.4 kWh/kg m COD) or the peroxone process (134.5 kWh/kg m COD).

The electrochemical oxidation of organic pollutants can take place in two ways: (i) direct electron exchange between the contaminant and the electrode surface, which can occur at relatively low potentials (i.e. prior to O_2 evolution); or (ii) by indirect in situ electro generation of catalytic species, which relies on the production of oxidizing species at the electrode that mediate the transformation of contaminants. The rates of direct electrolysis are affected by diffusion limitations, slow reaction kinetics, and a decrease in the catalytic activity of the electrode in the presence of dissolved solutes (i.e. poisoning) [51].

The effectiveness of electrochemical oxidation of organic pollutants depends largely on the properties of the anode material, such as the O_2 overpotential and adsorptive properties of the electrode surface [52–54]. Moreover, the reaction time, electrode separation distance, and electrode area might control the efficiency of EOC removal from wastewater [55].

Compared with conventional methods, the EK process has several advantages, such as ease of operation, short retention time, environmental compatibility, high-efficiency degradation, the potential for a high degree of automatization, robust performance, and the ability to adjust to variations in the influent composition and flow rate. However, the application of electrochemical treatment has been slowed by the relatively high costs of electrodes and concerns about toxic byproducts in the treated water [43].

6.2 Electrochemical Reactor for EOC Removal in WWTPs

A research study was carried out, aiming to investigate the electrooxidation performance of four different EOCs (Table 6.1) as a model for these experiments. The suitability of the electrode material and current density were studied, including sulfamethoxazole, carbamazepine, 17α-ethinylestradiol, and diclofenac from a real effluent sample. This investigation was undertaken to extend the knowledge of electro-degradation of EOCs in real effluents using different anode materials (graphite and Pt/Ti electrodes) and is part of the work carried out by the team and presented in [56]. The EOCs selected for the study include antibiotics, psychiatric drugs, hormones, and non-steroidal anti-inflammatory drugs that have been reported in rivers, lakes, and reservoirs around the world [10, 57–59]. In addition, all the EOCs present different physicochemical characteristics (e.g. solubility, octanol-water partition coefficient; Table 6.1) to give a representative study of EOC removal.

6.2.1 Experimental Design

Electrochemical experiments were carried out in a cylindrical reactor made of Plexiglas, 10 cm long and with an internal diameter of 8 cm (Figure 6.5). Electrodes were installed 2.5 cm from the middle of the reactor (5 cm apart from each other). The power supply (Hewlett-Packard E3612A) was used to maintain constant DC.

The vertical reactor was tested in a continuous flow mode with effluent at 2 ml min^{-1}. Two different anode materials – Pt/Ti (platinized coated titanium; length 5.5 cm, diameter 3 mm; Permascand®) and graphite (99.9995% metals basis; length 5.5 cm, diameter 3 mm; AlfaAesar) – were tested with a fixed Pt/Ti cathode. In addition to the effect of the anode material, two different current intensities were tested: 25 mA and 100 mA. Before EK treatment, the effluent was spiked with 3 mg l^{-1} of each contaminant.

6.2.1.1 Analytical Methodology

Sulfamethoxazole, carbamazepine, diclofenac, and ethinylestradiol standards with high purity grade (>97%) were purchased from Sigma-Aldrich (Steinheim, Germany). The effluent samples were pre-cleaned/concentrated by soli-phase extraction (SPE) using Oasis HLB 500 mg (Waters; Saint-Quentin En Yvelines Cedex, France). The cartridges were placed in an SPE manifold connected to a

Table 6.1 Chemical structure and properties of emerging organic contaminants.

EOCs	Formula	Log K_{ow}	pKa	Solubility in water (mg l^{-1})	Category
Sulfamethoxazole (SFM)	$C_{10}H_{11}N_3O_3S$	0.89	5.7	610	Antibiotic
Carbamazepine (CBMP)	$C_{15}H_{12}N_2O$	2.45	13.9	18	Anticonvulsive
17α-ethinylestradiol (EE2)	$C_{20}H_{24}O_2$	3.67	10.3	11.3	Estrogen
Diclofenac (DCF)	$C_{14}H_{11}Cl_2NO_2$	4.51	4.15	2.37	Anti-inflammatory

Sources: PubChem, http://pubchem.ncbi.nlm.nih.gov; Sigma-Aldrich, Inc., www.SigmaAldrich.com.

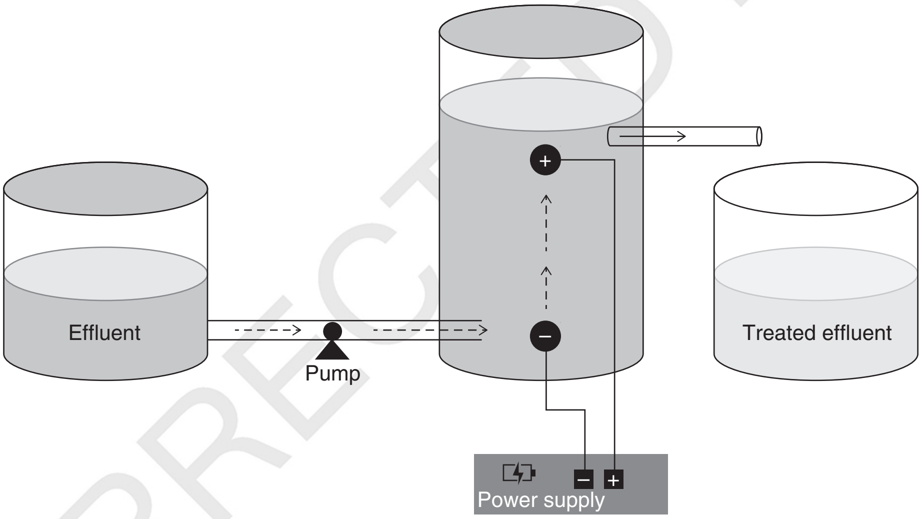

Figure 6.5 Electrochemical reactor design.

vacuum pump and operated as follows: conditioned by washing with 3 × 6 ml of MeOH, followed by re-equilibrium with 3 × 6 ml of Milli-Q water; for EOC enrichment, samples were acidified to pH 2 before extraction (nitric acid; deionized water, 1:1) and filtered through a 0.45 μm MF filter; 200 ml of the sample was passed through the cartridge at a flow rate of approximately 10 ml min^{-1}; then, the cartridges were dried for about 2 minutes by vacuum; finally, the extracts were eluted with two × 6 ml of MeOH. The samples were filtered before analysis through FILTER-LAB® polytetrafluoroethylene (PTFE) syringe filters (pore size 0.45 μm), previously passed through methanol. The EOC analysis was carried out by high-performance liquid chromatography (HPLC) with a diode array and fluorescence detectors (HPLC–DAD-FLD), 1260 Infinity II LC Systems (Agilent 1100

Series Technologies, USA) equipped with a quaternary pump and auto-sampler (1260). The RP-18e column (Chromolith High Resolution, 100 × 4.6 mm; VWR, Darmstadt, Germany) was used for analyte separation. LC OpenLab software was used for data processing.

6.2.2 Electrokinetic Reactor Operating in a Continuous Vertical Flow Mode

The initial effluent sample presented an alkaline pH (~8.6) and conductivity of ~1.8 mS cm^{-1}, and all the parameters were within the Portuguese legal limits for discharge into water bodies (DL 236/98). The pH, conductivity, and voltage values after EK treatment are listed in Table 6.2. The pH of the effluent had the tendency to decreases lightly, primarily when the higher current intensity was tested and when a graphite anode was used. The conductivity slightly decreased for the lowest current intensity and remained constant when applying a higher current intensity due to the greater production of ions in the electrode. The presence of Cl^- and other inorganic ions in the effluent yielded sufficient conductivity for direct EK treatment without adding any salt as supporting electrolyte. In both cases, using graphite or Pt/Ti as an anode, the voltage increased when higher current intensity was applied due to greater hydroxide ion generation.

Figure 6.6 shows the removal of the selected EOCs after EK treatment with low current intensity (25 mA) and with the current intensity increased four times (100 mA) for the two anode materials tested. An initial effluent screening was carried out, and the concentration of the target EOCs was below the analytical detection limits.

Compared with a control (without applied current), the effect of the lowest current applied (25 mA) promoted the removal of between 5 and 41% of EOCs; when the current intensity was increased to 100 mA, removal increased 10–36%. Regarding the differences among the contaminants for the two tested current intensities, CBMP and DCF showed the lowest level of removal. The compound's molecular structure has a strong influence on the success of electrochemical removal. Compounds characterized by the presence of electrophilic halogen groups with a negative inductive effect at the aromatic ring or by the absence of nucleophilic substituents with an activating effect on the aromatic ring like DCF are more recalcitrant because they

Table 6.2 pH, conductivity, and voltage drop after EK treatment.

Current intensity (mA)	Anode	pH	Conductivity (mS cm^{-1})	Voltage (V)
25	Graphite	8.11	1.72	7.2–7.0
	Pt/Ti	8.51	1.63	6.9–7.0
100	Graphite	7.25	1.85	14.8–16.7
	Pt/Ti	7.46	1.85	14.8–16.4

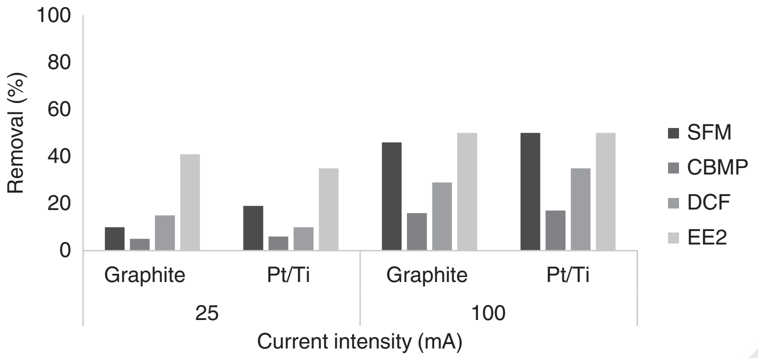

Figure 6.6 Removal (%) of EOCs after electrochemical treatment in a vertical continuous-flow reactor, applying different current intensities and anode materials.

decrease the reactivity toward oxidant agents and active chlorine species present in effluents [60].

- ***Current intensity***
  In several studies, current intensity is reported to affect electrochemical oxidation efficiency as it is the driving force of the reaction. The results from this study showed that EOC removal was enhanced by increasing current intensity. SFM removal increased by 36% when 100 mA were applied. Increasing current intensity promotes the generation of more OH, which is responsible for organic oxidation; hence, greater EOC removal can be expected in the tested conditions. Other research also found that an increase in current intensity enhances contaminant removal. For example, in [61], the effect of current density on the removal rate of COD of wastewater with sulfamethoxazole and trimethoprim (two well-known antibiotics) was investigated, and the results showed that COD removal efficiency increased when the current density increased from 10 to 100 mA cm^{-2}. However, when increased indefinitely, the current during EK treatment is not always proportional to the removal rate. The rate of parasitic reactions is also promoted, which leads to decreasing current efficiency and, consequently, less contaminant removal [47]. It is important to regular the amount of oxidizing species produced, taking into account the feasibility of the process in terms of electrical charge consumed and/or energy consumption [47]. In addition to energy dissipation, high current intensities can shorten the lifetime of the electrodes [62].
- ***Anode material***
  To improve process efficiency, several anode materials have been tested and show varied performance. In the tested conditions, no differences were found in terms of EOC degradation for the two tested anode materials, graphite and Pt/Ti. EK uses the electron as the primary reagent for contaminant removal: the generation of $^{\bullet}$OH from water oxidation at anode is crucial for EOC removal. Graphite and Pt/Ti are both considered active electrodes [63], and the electrogenerated •OH is expected to be converted in “adsorbed oxygen,” which is consumed in the oxidation of organic compounds with the formation of selective oxidation products and

in an easy oxygen evolution [64]. Even though no differences were found between the two anodes in the tested conditions, the Pt electrode showed better performance than graphite. Some differences were also found for SFM and DCF removal in previous research such as [65]. The authors attributed the differences to the different adsorptions of $^{\bullet}$OH on these electrodes: due to Pt, the $^{\bullet}$OH are weakly adsorbed and have lower adsorption on the Pt surface. Consequently, they are very reactive and effective toward oxidation due to the faster reactions with all organics arriving at the surface and in the anode's vicinity. On the other hand, graphite has more $^{\bullet}$OH strongly adsorbed on its surface; thus it is less reactive toward EOC degradation [65].

After EK treatment, the graphite electrode showed signs of corrosion due to the effect of the applied current. Higher current could lead to electric energy transfer to thermal energy and result in a larger invalid consumption of the given charge. Even though high current intensity caused the electrode material to corrode, side reactions including oxygen evolution could also happen simultaneously, and no differences between the two electrodes in terms of EOC removal were registered for the tested conditions [66].

- ***Flow mode***

The effect of current intensity can also be related to the continuous flow mode present in this work, which according to [64] is strongly interrelated, so they must be considered together. A continuous flow mode influences the direct oxidation of EOCs by the contact between electrode and effluent solution. In the vertical EK flow reactor, the effluent was in a continuous flow mode, passing first through the Pt/Ti cathode electrode, where reduction reactions take place, and going toward the anode, where $^{\bullet}$OH is generated. The oxidation of the organics by $^{\bullet}$OH generated from the water oxidation is so fast that the rate-determining step is the mass transport from the bulk solution to the anodic surface. When the rate of the mass transfer of the organic to the anodic surface is dramatically lower than the rate of oxidation, the concentration of the pollutant at the anodic surface/reaction layer is close to zero, and the oxidation process is under mass-transfer control [64]. Considering that the electrochemical oxidation of organics is limited by mass transport, high flow rates in the reactor might increase the mass transfer, thus allowing enhanced performance. If oxidation takes place by indirect electrolysis, high flow rates are reported to favor removal, meaning the oxidation is a diffusion-controlled process [67].

The present results showed that electrochemical degradation is a promising method for EOC removal, but operational parameters need to be optimized: for example, by changing the flow mode and current intensity and testing different electrode materials. Experiments in batch mode were carried out by the team, and greater removal (> 90%) was achieved [56]. The results presented in [56] also show that in addition to the influence of the batch and flow mode, the electrode shape and material are key to a cost-efficient process. Greater EOC removal was achieved in a batch-mode system, with both the electrode's shape and material proving to be important parameters to improve the EK process, not only for removing EOCs but also to make the process more efficient in terms of energy consumption.

6.3 Conclusions

To limit the presence of EOCs in the environment, efficient technologies should be implemented in WWTPs and stricter environmental quality standards should be established. The removal of EOCs with different physicochemical characteristics represents a real challenge in wastewater treatment. Research of electrochemical technologies to remove EOCs has been increasing, and the results show that treatment efficiency depends on reactor design and operational parameters such as flow mode and electrode material. The use of electrochemical technologies to remove EOCs from wastewater is a promising technology with the potential to reduce the environmental and human risks associated with the spread of contamination.

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