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Editorial

Current and Future Trends in Environmental Electrochemistry for Wastewater Treatment

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In recent years, the demand for high-quality water has constantly been increasing, while at the same time, the legislations regarding wastewater reuse are becoming stricter. Among the scientists and engineers involved in managing and treating water and wastewater, it is almost universally accepted that biological treatment methods are usually the most preferred as they are usually the most environmentally friendly solution [1]. However, biological methods cannot be used in the case of wastewater toxic to microorganisms. At the same time, in recent years, the problem of persistent micropollutants has arisen, which are particularly difficult to biodegrade [1].

In order to overcome the obstacles of biological systems, many researchers have suggested the environmental applications of electrochemistry as a promising solution [2–4]. The application of electrochemistry in the treatment of water and wastewater has led to the development of technologies such as electrochemical oxidation, electrocoagulation and the development of combined processes such as the electro Fenton process [2–4].

More specifically, this Special Issue aims to highlight new applications of electrochemistry to address different environmental problems related to water purification.

Electrocoagulation is one of the oldest electrochemical processes with industrial application. The work of Alam et al. [5] is an extended literature review on the use of the electrocoagulation process to treat pharmaceutical compounds. The critical review includes the effect of the operating parameters, the electrode materials and the configuration/geometry of the reactors, the combination of electrocoagulation with other technologies, and the estimated costs. The researchers suggest that future research must focus on using renewable energy to reduce the environmental and energy impact and the conduction of more studies on its application to real/industrial wastewater. Electrocoagulation is also the focus of another study in this Special Issue [6], this time for the removal of fluoride, which can lead to significant health problems. The researchers analyzed the mechanism of fluoride removal and the kinetics governing the process. The review also included the factors that affect performance, such as fluoride concentration, pH, the presence of other ions, and conductivity. Particular emphasis was given to studying operation parameters (current, treatment time, geometry and type of reactor, and electrode material). It is worth noting that according to the researchers, the successful implementation of the process beyond the operating parameters depends significantly on floc separation techniques. After estimating and comparing the treatment cost from existing units, the researchers concluded that widespread industrial application requires the development of new electrochemical reactors that will increase efficiency and reduce energy requirements. At the same time, future work should be directed to the study of the use/recycling of the produced sludge, mainly in the construction industry.

The removal of metals from industrial wastewater is another area of application of electrochemistry. Moosazade et al. [7] examine the removal of lead (Pb), a toxic metal, from direct osmosis concentrate using perforated aluminum electrodes mounted in an electrocoagulation–flotation cell (PA-ECF). The researchers studied and optimized the effect of the main operating parameters (current density, processing time) using factorial design, and the optimized Pb removal reached 97.8% after 77.7 min of applying 0.9 A. At the same time, the required energy was calculated as 0.25 kWh/m^3 of wastewater, and the cost equal to 0.423 USD/m^3. Interestingly, the optimal conditions were also applied to real metallurgical industry wastewater instead of synthetic solutions and resulted in 94.2% Pb removal, confirming both the industrial application and the validity of the model used.

Several published works demonstrated the efficiency of the anodic electrochemical oxidation of different pharmaceutical compounds using different electrodes such as Dimensionally Stable Anodes (DSA) electrodes such as IrO_2, SnO_2 [2,3,8], or non-active electrodes such as Boron Doped Diamond (BDD) [9]. Despite the promising results, one of the biggest problems of electrochemical oxidation is the mass transfer limitations, hence the need for larger electrode surfaces, which significantly increases the cost. Various strategies have been proposed to address this problem. For example, some researchers suggest the use of 3D electrodes or the use of particle electrodes from relatively inexpensive materials [4] that will allow pollutants to oxidize over significantly larger surfaces.

Another approach is the work of Zwane et al. [10], which proposes the combination of electrochemical oxidation with the conventional Fenton process through the in situ electrosynthesis of hydrogen peroxide in a carbon felt cathode (Electro Fenton process). Indeed, the combined process showed better results than electrochemical oxidation by completely removing the pharmaceutical tetracycline in less than 30 min under optimal conditions, while the removal of total organic carbon reached 69% in 4 h using 0.05 mM Na_2SO_4 as the supporting electrolyte at pH 3 and 120 mA current, while Ti_4O_7 was served as the anode. Intermediate products, as well as the toxicity of the combined process, were also investigated. Toxicity decreased for both 20 and 50 mg/L Tetracycline solution using the bacteria *Vibrio Fischeri* as indicators

Another combination of electrochemical oxidation with the Fenton process has also been investigated by Deng et al. [11] to treat industrial-pharmaceutical wastewater. The researchers followed an interesting approach. Instead of adding Fe^{2+} iron salts, they studied the magnetically decorating zero-valent iron (ZVI) on a RuO^2-IrO_2/Ti electrode. In this way, zero-valent iron can be a constant source of Fe^{2+} during electrochemical treatment.

By applying the maximum voltage (12 V), the proposed Electro-Fenton system based on ZVI-RuO^2-IrO_2/Ti electrode removed 78.69% of Chemical Oxygen Demand (COD) and 76.40% of Total Organic Carbon (TOC) in 12 h of treatment of pharmaceutical wastewater with initial COD 5500 mg/L. This efficiency was significantly higher than the experiments without zero-valent iron or hydrogen peroxide. At the same time, the proposed system removed 100% of the total phosphorus (TP) in 12 h using a lower voltage (3 V). Interestingly, the BOD/COD ratio was increased from 0.21 to 0.42, indicating that the proposed process could be used as pretreatment followed by a biological method.

Future Trends

In summary, electrochemistry remains particularly attractive for treating different types of non-biodegradable wastewater [12]. Some processes, such as electrocoagulation, are quite close to many industrial applications, while others are several steps away from the widespread application. Nevertheless, future research should focus on optimizing the process and reducing costs, which can be achieved either by developing new reactors or combining them with other biological or physicochemical methods. At the same time, an important issue that is expected to concern the final users is the disposal of the produced sludge, especially in light of the circular economy and minimizing the total cost. On the other hand, in processes such as electrochemical oxidation, there are various future research directions, such as the development of new materials with increased activity or the combination with other processes, where the existence of synergy can significantly increase efficiency and, therefore, the viability of the combined or hybrid process. In all electrochemical applications, their coupling with renewable energy sources or even with microbial cells is expected in the future to lead to integrated systems with a significantly reduced environmental and energy footprint.

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