Electrochemical processes for the remediation of wastewater and contaminated soil: emerging technology

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The review aims at providing an overview of electrochemical processes used for accomplishing the remediation of industrial wastewater, particularly electrooxidation processes and electrocoagulation. The applicability of these technologies for the remediation of contaminated soil is also discussed. The use of electrochemical process as a pre-treatment step to enhance the biodegradability of wastewater containing recalcitrant or inhibitory compounds can potentially be justified due to the formation of intermediate, which is easily degraded in subsequent biological treatment. The enhanced degradation of wastewater may be attributed to the electrochemical oxidation of the organic compounds present in the aqueous phase to simple molecules, which may be easily biodegraded. The principle of electrooxidation process, involved in the remediation process was described along with specific applications. The application of electrocoagulation process for wastewater treatment is also reviewed.

Keywords: Electrochemical processes, Electrooxidation, Biodegradability, Electrocoagulation, Wastewater, Contaminated soils.

Introduction

The ecosphere continues to be challenged by the increasing amount and variability of toxic contaminants that are emitted by industrial activities like manufacture of chemicals, including many pesticides, herbicides, chemicals and pharmaceuticals, dye stuff units, and meat packing units, which are more saline. Such environmental contaminants are becoming more widespread as the pace of industrial activity accelerates, especially in the developing countries, and also as a consequence of the difficulties in restricting the emissions of industrial activity. Particularly, rivers, canals, estuaries, and other water bodies are being constantly polluted due to indiscriminate discharge of industrial effluents. Water has acquired increasing importance due to its two unique characteristics: high specific heat capacity and high solvent power with respect to many inorganic and some organic substances. As a consequence of these two factors; water can serve as a heat reservoir, cooling agent, steam sources, etc., and is subsequently returned to the environment at a high temperature. On the other hand, water in its function as a reaction medium, or even a reaction partner, has now developed into the most significant source of wastewater in any industry, in particular, chemical and pharmaceutical processes. Improper disposal of these aqueous wastes may increase the probability of contamination of water resources and is main health and environmental concern due to its high toxicity. There is, therefore, an urgent need to develop innovative, more effective, and inexpensive technologies for treatment of wastewater. In this review, we wish to address an overview of electrochemical processes such as: (i) Electrooxidation processes and (ii) Electrocoagulation to accomplish treatment of industrial wastewater.

Industrial Wastewater Treatment

Treatment plants intended for the purification of any industrial wastewater utilize a combination of processing techniques such as:

Physical Treatment — Intended for the elimination of undissolved substances, including screening, clarification, and filtration.

Physico-chemical/Chemical Treatment — Intended to treat dissolved and suspended pollutants by means of
physico-chemical processes which include neutralization, coagulation, ion-exchange, chemical precipitation, chemical oxidation, carbon adsorption, ultra filtration, reverse osmosis, electro-dialysis, volatilization or gas stripping. This treatment demands transportation, storing, and handling of hazardous chemicals and leads to the generation of toxic sludge\textsuperscript{16}. 

**Advanced Oxidation Processes** — Advanced oxidation processes involve the chemical, photochemical or photocatalytic production of hydroxyl radical (\(\cdot\)OH) [Eq. (1 and 2)], which acts as a strong oxidizing agent able to react with organics, yielding dehydrogenated or hydroxylated derivatives\textsuperscript{17-21}. 

\[
\begin{align*}
\text{H}_2\text{O}_2 & \rightarrow \cdot\text{OH} + \cdot\text{OH} \quad \text{(1)} \\
\text{H}_2\text{O} & \rightarrow \cdot\text{H} + \cdot\text{OH} \quad \text{(2)}
\end{align*}
\]

Recently the use of Fenton reaction to generate hydroxyl radicals to degrade organic contaminants has also received lot of attention\textsuperscript{22,23}. But these processes are not desirable, because of the high cost of equipment and operating costs and also the secondary pollution arising from the residual chemicals and finally the low efficiency.

**Biological treatment** — Intended for the removal of dissolved substances, in the course of which colloidally dispersed materials are also destabilized and flocculated. Biological treatment involves the biotechnological application of processes that occur in nature, which include aerobic and anaerobic processes. In aerobic process, organic component of effluent is oxidized to carbon dioxide (mineralization) or some other metabolic intermediate products in the presence of dissolved oxygen, whereas in anaerobic metabolism, organic substances are first converted to carboxylic acids (acidification) and then disproportionate to carbonic acid, methane and hydrogen (methanogenic fermentation) in the absence of oxygen\textsuperscript{15}. The advantage of biological treatment is the enormous adaptability of microorganisms to a wide variety of substrate media\textsuperscript{7,24}, but this is a long term treatment in large physical areas and leads to the generation of non-biodegradable, soluble, and cellular residues and also the high salinity of the effluent inhibit the microbial growth. Furthermore, high molecular weight fractions present in some types of aquatic effluents found in several industries tend to be resistant to biodegradation and inhibition\textsuperscript{25-27}. Hence the overall efficiency of the biological treatment, even after employing well-acclimatized microorganisms is far from satisfactory\textsuperscript{28}. It is essential to enhance the biodegradability of the effluent by breaking the refractory chemicals prior to the biological process to enhance the biodegradability which can be achieved by proper application of physico-chemical or chemical or advanced oxidation methods. Also, recent literature indicates the applicability of electrochemical process as an attractive alternative for application prior to biological methods.

**Electrochemical Processes**

Recent progress in effluent treatment has lead to the development of electrochemical techniques\textsuperscript{29-37}, which may offer an attractive alternative and more environmentally friendly process for treating aqueous streams containing organic compounds. Electrochemical processes are probably the most adequate tools in the aqueous effluent treatment, which are ideally suited to the present age. The process will not require chemical additions and indeed electrons are the only reactants added to the process to simulate reaction. These processes include electrooxidation and electrocoagulation. 

(i) **Electrooxidation** — Electrooxidation may offer an attractive alternative\textsuperscript{38-43}, for treating aqueous streams containing the organic compounds, via simultaneous evolution of oxygen at an anode surface, which is probably the most adequate tool in the aqueous effluent treatment, ideally suited to present age where environmental considerations are always to the fore\textsuperscript{44}. Electrooxidation is a mediated reaction and occurs via oxygen atom’s transfer from water in the solvent phase to the oxidation product. The overall process of anodic oxygen transfer may be represented by the generic reaction\textsuperscript{45} [Eq. (3); where R is organic reactant and RO\(_x\) is oxidation product]. On the other hand, R may mineralize, according to Eq. (4); known as combustion reaction.

\[
\begin{align*}
\text{R} + \text{XH}_2\text{O} & \rightarrow \text{RO}_x + 2\text{XH}^+ + 2\text{xe}^- \quad \text{(3)} \\
\text{R} + \text{XH}_2\text{O} & \rightarrow \text{X/2 CO}_2 + 2\text{XH}^+ + 2\text{xe}^- \quad \text{(4)}
\end{align*}
\]

These processes were investigated for different organic compounds\textsuperscript{46,47}, in which, it is impossible to suppress the most side reaction, i.e. the anodic oxidation of water to give O\(_2\), and the consequence is that only low current yields can be achieved. Further disadvantage of direct electrochemical oxidation is
the low miscibility of most organics with water. As a result, mass transfer from the bulk solution to the anode is hindered and the achievable space-time yields are low. Also, electrolysis often consumes much energy, especially in dilute wastewater treatment processes. For this reason the efficient electrochemical methods for water purification based on the indirect electrooxidation of contaminants involving electrogeneration of strong oxidants is now in progress which is a more reliable technology for the degradation of toxic organic wastes and provides better results over the direct electrooxidation. In this process the waste is oxidized in the bulk solution by a mediator, mostly a transition metal in a higher oxidation state. After waste oxidation in the bulk solution the reduced mediator is reoxidized at the anode, which is capable of oxidizing further organic molecules. The mechanism proposed for this process of organic compounds in aqueous solutions presents, as the first step the disadvantage of water which leads to the "OH adsorbed on the electrode surface, then MOX coating [Eq. (5)], then MOX species can be formed from hydroxyl radicals in the active sites of the MOX coating [Eq. (6)], finally, this physisorbed species oxidises the organic molecules [Eq. (7)].

\[
\text{MO}_X + \text{H}_2\text{O} \rightarrow \text{MO}_X(\cdot \text{OH}) + \text{H}^+ + e^- \quad \ldots(5)
\]

\[
\text{MO}_X(\cdot \text{OH}) \rightarrow \text{MO}_{X+1} + \text{H}^+ + e^- \quad \ldots(6)
\]

\[
\text{MO}_{X+1} + R \rightarrow \text{MO}_X + \text{RO} \quad \ldots(7)
\]

A second possible reaction path is also considered, in which the organic compound is mineralized [Eq. (8)], which is more likely to occur on higher oxygen overpotentials that contain PbO$_2$, SnO$_2$ or Sb$_2$O$_5$.

\[
[\text{MO}_X(\cdot \text{OH})]_Y + R \rightarrow 2\text{YCO}_2 + 2\text{YH}^+ + 2\text{Ye}^- + \text{YMO}_X \quad \ldots(8)
\]

Thus the pollutants can be treated with electrogenerated H$_2$O$_2$ in a two-compartment cell, in which the hydrogen peroxide is continuously supplied to the cathodic compartment from the two-electron reduction of sparged oxygen on graphite or reticulated vitreous carbon cathodes [Eq. (9)].

\[
\text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O}_2 \quad \ldots(9)
\]

Also the wastewater can be treated using an undivided electrolytic cell containing a Pt anode and a carbon-polytetrafluoroethylene (PTFE) O$_2$ fed cathode where H$_2$O$_2$ is electrogenerated [Eq. (9)]. In these processes the pollutants can be mainly destroyed by the combined action of electrogenerated •OH [Eq. (10)] at the anode$^{53}$. Therefore the processes are called advanced electrochemical oxidation processes (AEOPs).

\[
\text{H}_2\text{O} \rightarrow •\text{OH}_{ads} + \text{H}^+ + e^- \quad \ldots(10)
\]

On the other hand the oxidizing power can be enhanced in an acidic medium by the addition of Fe$^{2+}$ to produce •OH, which can be produced by a well known Fenton’s reaction between ferrous ion and hydrogen peroxide in the medium [Eq. (11)], and the process can be treated as electrochemical Fenton treatment$^{54}$.

\[
\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe(OH)}^{2+} + •\text{OH} \quad \ldots(11)
\]

This catalytic reaction is propagated from Fe$^{2+}$ regeneration, which takes place by the reduction of Fe$^{3+}$ species with H$_2$O$_2$ [Eq. (12)] and also from the reaction of Fe$^{3+}$ at the cathode [Eq. (13)].

\[
\text{Fe}^{3+} + \text{H}_2\text{O}_2 \leftrightarrow [\text{Fe-O}_\text{H}]^{2+} \rightarrow \text{Fe}^{2+} + \text{HO}_2^* \quad \ldots(12)
\]

\[
\text{Fe}^{3+} + e^- \rightarrow \text{Fe}^{2+} \quad \ldots(13)
\]

Under an UV irradiation the mineralization process can be accelerated by the photolysis of Fe$^{3+}$ complexes and by the enhancement of Fe$^{2+}$ regeneration due to the additional photoreduction of Fe$^{3+}$ species via photo-Fenton reaction [Eq. (14)], which can takes place within the wavelength range 320-480 nm.

\[
\text{Fe(OH)}^{2+} \rightarrow \text{Fe}^{2+} + •\text{OH} \quad \ldots(14)
\]

These reactions lead to a constant catalytic Fe$^{2+}$ concentration lower than 0.05 mM in the solution after 15 min of electrolysis. Consequently the electrogenerated H$_2$O$_2$ can also be oxidized to O$_2$ at the anode$^{55}$ [Eq. (15 and 16)].

\[
\text{H}_2\text{O}_2 \rightarrow \text{HO}_2^* + \text{H}^+ + e^- \quad \ldots(15)
\]

\[
\text{HO}_2^* \rightarrow \text{O}_2 + \text{H}^+ + e^- \quad \ldots(16)
\]

Usually the electrooxidation process can be carried out in an electrochemical cell. The schematic diagram of the experimental set up is shown in Figure 1. The rate of degradation of any organic compound can be assessed by measuring the per cent
of COD reduction or by determining the intensive current efficiency (ICE)\textsuperscript{56} through the measurement of COD by the standard method (closed reflux/photometry), while the organic compound present in effluent and its oxidation products can be carried out for each run or for certain time interval with high performance liquid chromatography (HPLC).

(ii) Electrocoagulation (EC) — Coagulation is a phenomenon in which the charged particles (a colloidal suspension) are neutralized by neutral collision with counter ions present in the coagulant added, and are agglomerated, followed by the process of sedimentation. Alum [Al\textsubscript{2} (SO\textsubscript{4})\textsubscript{3}.18H\textsubscript{2}O] is a coagulant which has been widely used for ages for the wastewater treatment. In the EC process the coagulant is generated \textit{in situ} by electrolytic oxidation of an appropriate anode material. In this process, charged ionic species are removed from effluent by allowing it to react: (i) With an ion having opposite charge, or (ii) With floc of metallic hydroxides generated within the effluent. The EC technology offers an alternative to the use of metal salts or polymers and polyelectrolyte addition for breaking stable emissions and suspensions\textsuperscript{57}. The technology removes metals, colloidal and solid particles, and soluble inorganic pollutants from aqueous media by introducing highly charged polymeric metal hydroxide species\textsuperscript{58-61}. These species neutralize the electrolytic charges on suspended solids and oil droplets to facilitate coagulation. This process involves three successive steps: (a) Formation of coagulants by electrolytic oxidation of the ‘sacrificial electrode’;

(b) Destabilization of the contaminants, particulate suspension, and breaking of emulsions; (c) Aggregation of the destabilized phases to form flocs. The mechanism of EC is highly dependent on the chemistry of the aqueous medium, especially conductivity. In addition, other characteristics such as, pH, particle size, and chemical constituent concentrations also influence the EC process. This can be explained with two specific examples involving aluminium and iron as coagulant aids.

(a) Aluminium — The electrolytic dissolution of the aluminium anode produces the cationic monomeric species\textsuperscript{62} such as, Al\textsuperscript{3+} and Al(OH)\textsubscript{2+} at low pH, which are transformed initially into Al(OH)\textsubscript{3} at appropriate pH values and finally polymerized to Al\textsubscript{n}OH\textsubscript{3n} (Scheme 1). However, depending on the pH of the aqueous medium, other ionic species such as, Al(OH)\textsubscript{2+}, Al\textsubscript{2}(OH)\textsubscript{4+}, and Al(OH)\textsubscript{4} may also be present in the system. These charged species could effectively remove the pollutants by adsorption to produce charge neutralization.

(b) Iron — Iron produces iron hydroxide, Fe(OH)\textsubscript{n} (where \textit{n} is 2 or 3), in an electrolytic system by oxidation\textsuperscript{63} (Scheme 2 and 3). The formed Fe(OH)\textsubscript{n} remains in the aqueous stream as a gelatinous suspension, which can remove the pollutants from effluent either by complexation or by electrostatic attraction, followed by coagulation. Wastewater containing Cr\textsuperscript{6+} (CrO\textsubscript{4}\textsubscript{2-}) ions can be removed by the EC technique using iron as the sacrificial anode. Also the use of Fe\textsuperscript{3+} as flocculation agent in wastewater treatment has considerable advantages because of its innocuity compared to Al\textsuperscript{3+} ions, which shows some toxic effects\textsuperscript{64}.

Generally the electrocoagulation can be carried out in a simple electrochemical cell, with single number of both the electrodes, but this is not suitable for effluent treatment since, for a workable rate of metal dissolution the use of electrodes with large surface area is required. This has been achieved by using the cells with monopolar electrodes, either in parallel or series connections. During the electrolysis the +ve side undergoes anodic reactions, while on –ve

\[
\text{Al} \rightarrow \text{Al}^{3+} (aq) + 3e^- \\
\text{Al}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Al(OH)}_3 + 3\text{H}^+ (aq) \\
n\text{Al(OH)}_3 \rightarrow \text{Al}_n\text{(OH)}_{3n}
\]

Scheme 1
Applicability of Electrochemical Processes for Remediation

In industry the economic factors usually decide the inclusion of a wastewater treatment system. Cooling water, which is not in need for treatment, is separated from that which does require treatment. If the effluent is requiring treatment containing non-biodegradable complex organic matter and fails to meet the quality specifications for electrochemical treatment, it must first be subjected to physical/physico-chemical pre-treatment, followed by primary sedimentation to enhance the degradability, after which it can be fed to electrochemical system. The typical representation of the flow diagram is shown in Figure 2.

The data acquired from the literature\textsuperscript{65} (Table 1), shows the efficiency of the different electrooxidation processes for treatment. The degradability (TOC removal) of 2,4-dichlorophenoxycetic acid (2,4-D) with an initial concentration of 230 ppm, is 10 per cent, and 11 per cent, 52 per cent, and 83 per cent by anodicoxidation and in the presence of electro-generated H\textsubscript{2}O\textsubscript{2}, electro-Fenton and photoelectro-Fenton processes respectively, at pH value close to 2.9 which reveals that the degradation rate is very slow for the substrate and its oxidation derivatives by anodicoxidation and slightly higher in the presence of electro-generated H\textsubscript{2}O\textsubscript{2} due to the reaction with H\textsubscript{2}O\textsubscript{2} and HO\textsuperscript{-} produced [Eq. (15)], whereas the destruction of these contaminants is notably accelerated when the solution contains Fe\textsuperscript{2+}. In fact the main oxidizing species in both processes is the absorbed \textsuperscript{1}OH generated in very small concentration by the anodic decomposition of water [Eq. (10)]. The increase in TOC removal observed for the electro-Fenton process can then be ascribed to fast reactions of pollutants with \textsuperscript{1}OH produced in the medium [Eq.
The electrochemical oxidation of an aqueous phenol via industrial wastewater became an advanced technology for treating electrooxidation processes and electrocoagulation for subsequent cheap biological treatment (Figure 2). Pollutants provides a valuable pre-treatment technique. Thus the partial oxidation of organic biorefractry easily degraded in subsequent biological treatment. Potentially be justified if the resulting intermediate is enhance the biodegradability of wastewater electrochemical process as a pre-treatment step to by an economical biological process. The use of stage (degrade to aliphatic carboxylic acids) followed high-energy consumption. It may be worthwhile to enhance the biodegradability of wastewater through electrochemical treatment. The activated carbon fibre (ACF) electrode was used by industry as further treatment of aqueous phenolic wastes. Lin et al., explored the effects of wastewater salinity, pH and current density, temperature, and initial concentration on treatment efficiency of electrochemical method. It was reported that at low or medium salinity, phenol removal is dominated by direct oxidation at the electrode surface but at high salinity indirect oxidation by hypochlorous acid is a major one. Johnson et al., reported the discovery of optimal electrocatalytic materials and conditions for rapid degradation of organic compounds to CO\(_2\) (g). It shows that the rates of anodic degradation for carboxylic acids can be increased by increasing the anode temperature in acidic media, and achieved the successful anodic degradation of cyanuric acid at Pt anode, which is known to be a stable end product in the photocatalytic degradations of s-triazines.

Saracco et al., carried the anodic oxidation of coumaric acid on a Pt-Ti electrode. The study indicated that the kinetics are enhanced by; increasing the temperature, enhancing current density, alternating electrode potential, lowering the initial pH, and dissolving Fe\(^{3+}\) ions. Galla et al., reported the mediated electrooxidation for the degradation of real pesticides, simulates for warfare agents, and industrial wastes, which succeeds with yields near to 100 per cent. Torres et al., studied the electrochemical oxidation of industrial wastewater containing 5-amino-6-methyl-2-benzimidazolone (AMBI) employing Pt anode due to electrolysis. This non-biodegradable effluent produces simultaneous oxidation of AMBI and chloride ions. Highly oxidative chlorine intermediate species enhanced the oxidation of AMBI. It was reported that, solution temperature, pH, and current density affect the degradation process. Complete mineralization after electrochemical treatment was readily achieved in the coupled fixed bed biological reactor.

The activated carbon fibre (ACF) electrode electrolysis process can successfully decolorize the number of dyes despite wide variety of the chemical structure and type. The colour removal ratio of solution is uniformly above 85 per cent and the TOC removal ratio ranged widely from 30-70 per cent.

In the last decade, electrocoagulation technology has been increasingly used in South America and Europe for treatment of industrial wastewater.

<table>
<thead>
<tr>
<th>Method</th>
<th>Applied current (mA)</th>
<th>Per cent TOC removal</th>
<th>ACE(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anodic oxidation</td>
<td>100</td>
<td>10</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>15</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>18</td>
<td>1.6</td>
</tr>
<tr>
<td>Anodic oxidation in the presence of electrogeneration of H(_2)(_2)O(_2)</td>
<td>100</td>
<td>11</td>
<td>4.7</td>
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<tr>
<td></td>
<td>300</td>
<td>23</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>450</td>
<td>26</td>
<td>2.5</td>
</tr>
<tr>
<td>Electro-Fenton process</td>
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<td>52</td>
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<td>73</td>
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<tr>
<td>Photoelectro-Fenton process</td>
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<tr>
<td></td>
<td>450</td>
<td>82</td>
<td>8.9</td>
</tr>
</tbody>
</table>

\(^a\)Apparent current efficiency

(11)], while in photoelectro-Fenton process the highest mineralization is due to the higher production rate of \(^{\cdot}\)OH [Eq. (14)] and/or additional photo-decomposition of several intermediates.

In fact, the complete oxidation of complex organic compound to final product CO\(_3\)\(_2\) by electrochemical treatment is uneconomical due to high-energy consumption. It may be worthwhile to treat the industrial wastewater to the biodegradable stage (degrade to aliphatic carboxylic acids) followed by an economical biological process. The use of electrochemical process as a pre-treatment step to enhance the biodegradability of wastewater containing recalcitrant or inhibitory compounds can potentially be justified if the resulting intermediate is easily degraded in subsequent biological treatment. Thus the partial oxidation of organic biorefractry pollutants provides a valuable pre-treatment technique for subsequent cheap biological treatment (Figure 2).

The electrochemical techniques such as electrooxidation processes and electrocoagulation were became as an advanced technology for treating the industrial wastewater. Boudenne et al., studied the electrochemical oxidation of an aqueous phenol via carbon black catalyst, which demonstrates the complete degradation of phenol and the process could be used by industry as further treatment of aqueous phenolic wastes. Lin et al., explored the effects of wastewater salinity, pH and current density, temperature, and initial concentration on treatment efficiency of electrochemical method. It was reported that at low or medium salinity, phenol removal is dominated by direct oxidation at the electrode surface but at high salinity indirect oxidation by hypochlorous acid is a major one. Johnson et al., reported the discovery of optimal electrocatalytic materials and conditions for rapid degradation of organic compounds to CO\(_2\) (g). It shows that the rates of anodic degradation for carboxylic acids can be increased by increasing the anode temperature in acidic media, and achieved the successful anodic degradation of cyanuric acid at Pt anode, which is known to be a stable end product in the photocatalytic degradations of s-triazines.

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containing metals and also used primarily to treat wastewater from pulp and paper industries, mining and metal-processing industries. Kopper and Ogutveren, reported the complete removal of nitrate from water using electrocoagulation, which has been accomplished accompanying with the precipitation of Fe(OH)₃ produced in water by soluble anode. In addition EC, has been applied to treat wastewater containing chemical and mechanical polishing waste, organic matter from landfill leachates, and deflourination of water.

Electrokinetics procedure is the application of direct electric current to soil, which is an emerging engineering technique for the remediation of contaminated soil for both metal and organic contamination. An electric current between electrodes inserted into the soil generates hydrogen ion at the anode and hydroxyl ions at the cathode, which moves into the soil by electromigration, forming a pH gradient. Facilitates movement of metals towards the cathode, where they are removed and collected. Anionic metal complexes, inorganic anions and negatively charged organics will migrate towards the anode while dipolar interactions between water molecules and soil surface lead to an electroosmotic flow of water towards the cathode, which is able to transport uncharged organics. The application of electrokinetics to the remediation of organic-contaminated soil has focused upon electroosmotic approaches for uncharged molecules such as cola tar constituents, including PAHs. The concept of moving the organic contaminant into an area containing degradative microorganisms is attractive because of the potential for movement into an inoculated degradative zone, dispersion from areas of high contaminations and release from sequestration in soil micropores. The coupling of electro kinetic movement of an organic contaminant, 2,4-D acid through soil and its biodegradation in situ has been demonstrated by Jackman and coworkers. Under an applied current density of 0.89 A/m², 2,4-D moved towards the bacteria and its concentration decreased. James et al., reported the partial reoxidation at a Ti/IrO₂ as the most satisfactory method for the remediation of nitrotoluene explosives.

Conclusions

The following conclusions are drawn from the study:

• The electrochemical methods such as electrooxidation processes and electrocoagulation form an attractive alternative, and are successfully applied for industrial wastewater treatment. They neither produce any undesired reaction co-products nor use toxic or hazardous materials.
• The chemical change in both methods, is brought about by the ability to add or remove electrons, a non-polluting reagent, from the chemical treatment or from a chemical species to be treated. This eliminates the use of redox reagents to carry out oxidation or reduction.
• The high degradation potential of the electrooxidation processes is ascribed to the production of oxidizing *OH in solution from electrogenerated H₂O₂, and is reported to be improved in comparison to that of chemical and photochemical methods.
• Electrooxidation processes as a pre-treatment step, enhance the biodegradability of wastewater containing recalcitrant or inhibitory compounds, by resulting intermediate is easily degraded in subsequent biological treatment.
• Electrochemical technique can be effectively used for the remediation of contaminated soil matrix.
• These techniques were also suitable for on-site treatment, especially in small-scale use.

References


