



**CEE 597T**

**Electrochemical Water and Wastewater Treatment**

**ELECTROCHEMICAL DISINFECTION,  
APPLICATIONS IN WATER AND  
WASTEWATER TREATMENTS**



- **Active anodes** (e.g., Pt, IrO<sub>2</sub>, and RuO<sub>2</sub>), which present low oxygen evolution overpotential, are good electrocatalysts for the OER and, consequently, lead to selective oxidation of the organic pollutants, also denoted, as *partial oxidation of organics or electrochemical conversion*.
- This is due to the fact that the electrogenerated species from water discharge at the anode are present as *chemisorbed “active oxygen”* (oxygen in the lattice of a metal oxide (MO) anode), limiting the amount of free-hydroxyl radicals.
- For “active” electrodes there is a strong interaction between electrode M and hydroxyl radicals. In this latter case, an oxygen transfer occurs between the hydroxyl radicals and the anode surface to form an oxide on the electrode surface. The couple MO/M can act as a mediator in the selective oxidation of organics, the surface redox.

- **Nonactive anodes** (e.g.,  $\text{PbO}_2$ ,  $\text{SnO}_2$ , and BDD), which present high oxygen evolution overpotential, are
  - poor electrocatalysts for the OER, and
  - direct electrochemical oxidation is expected to occur for these electrodes.
  - They present no higher oxidation state available and
  - the organic species are directly oxidized by *nonadsorbed hydroxyl radicals*, giving *complete combustion* (so-called electrochemical combustion or incineration)
- For “nonactive” electrodes there is a weak interaction between electrode M and hydroxyl radicals ( $\bullet\text{OH}$ ). In this case, the oxidation of organics is mediated by hydroxyl radicals. This reaction occurs in competition with oxygen evolution by hydroxyl radical discharge. This case is typical for boron doped diamond electrodes.

- The comparison of the oxygen overpotential shows that lead dioxide, tin dioxide, and BDD have electrochemical windows larger than that of platinum.
- This means that under anodic polarization in the region of water oxidation, the production of strong oxidative species that are weakly adsorbed on the electrode surface are particularly active for oxidation. From this results a remarkable electrocatalytic activity toward organic compounds.
- In other words, *the oxygen overpotential increases as the adsorption strength of hydroxyl radicals on the electrode surface decreases*. So, electrode materials that favor the chemisorption emphasize the selective oxidation, like platinum, IrO<sub>2</sub>, or RuO<sub>2</sub>.
- Conversely, BDD exhibits a lower adsorption capacity, and hydroxyl radicals which are quasi free on the electrode surface react very quickly and strongly, and favor complete mineralization.

## *The Oxygen Evolution Reaction (OER)*

- The OER is the primary electrochemical reaction in water electrolysis. The standard electrode potential for this reaction at 25°C is 1.299 V vs the normal hydrogen electrode (NHE) in acid media and 0.401 V in alkaline media. The pertinent reactions are
- $2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-$  (acid media)
- $4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^-$  (alkaline media)
- According to the thermodynamics, all organic pollutants should be oxidized at potentials below the theoretical potential of OER ( $E^0 = 1.23$  V).
- However, the complete mineralization of pollutants can only be achieved for simple organic molecules while using highly reactive catalysts such as Pt.
- In this regard, there is a need to use electrocatalytic anodes with the high overpotential toward OER.

# Disinfection

- Disinfectants action usually implies cell lysis, that is, the dissolution of the cell membrane of the target organism, thus causing a change in cell permeability and inhibition of enzyme activity.
- The added chemicals affect membrane functions—they change osmotic pressure, permeability, and the transport processes of molecules and ions through the membrane while also inhibiting metabolic processes, bio-oxidation, and cell division.

# How Can Electrochemistry Be Useful for Disinfection?

- EO in electrodisinfection is based on the anodic generation of strong oxidants such as oxygen, ozone, or hypochlorite during water electrolysis.
- Similar to conventional chemical disinfection, electrodisinfection can be used for the removal and deactivation of different microorganisms from water and often it is more efficient than chemical disinfection.
- The main advantages of electrochemical disinfection compared with conventional chemical disinfection is to
  - I. keep the working areas required for the storage and dosage of chemicals substances;
  - II. compact reactors allowing to operate in situ the main line of treatment facilities and
  - III. no side generation of hazardous intermediates, which are typical for chemical disinfection.

- In electrochemical disinfection processes, the production of oxidants (disinfectants) may occur directly by
  - i. water discharge (i.e., hydroxyl radicals, ozone),
  - ii. dissolved species (i.e., active chlorine or hydrogen peroxide via oxygen reduction), or
  - iii. anode dissolution (i.e., ferrate).

Types and concentrations of the formed oxidants strictly depend on the adopted operating conditions, mostly on the used electrode material.

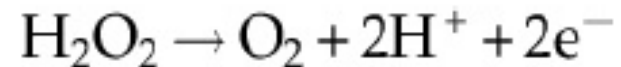
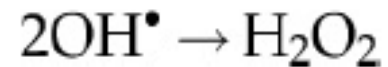
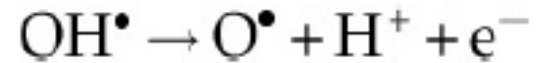
- The main advantage provided by electrochemical disinfection is the possibility of producing the species involved in situ, thus avoiding all the hazards correlated to the manipulation of highly concentrated oxidants, very often without a requirement of additional chemicals.



# Electrodisinfection by reactive oxygenated species

- In particular, diamond electrodes exhibit high overpotential for water oxidation, allowing the electrogeneration of hydroxyl radicals directly from an aqueous solution.
- Because  $\text{OH}\cdot$  radicals are scarcely adsorbed at the BDD surface, they are quickly desorbed and may react either with oxidizable compounds or with each other to give oxygen.
- Moreover, other bulk oxidizing agents such as hydrogen peroxide and ozone can be produced.
- Thus, reactive oxygenated species (ROS) may be generated during water oxidation, which can be exploited for a *chlorine-free disinfection process*.

- The global process of OER at this electrode material can be sketched as:



- Due to their high reactivity, the radicals desorbed from the electrode surface remain confined near the anode in a thin layer of solution  $\delta r$ , (thickness of 10–40 nm), where they rapidly give rise to oxygen or other *reactive oxygen species* (ROS) such as ozone or hydrogen peroxide.

# Electrodisinfection by oxygen gas

- Anodic generation of oxygen, which shows some germicidal activity, is used mainly for the removal of bad odor from water in small applications where the generation of chlorine species is undesirable.
- The most commonly used electrodes for oxygen evolution are Pt-containing anodes.
- Anodic generation of oxygen is shown in the following equations:



# Electrodisinfection by chlorine gas and hypochlorite ions



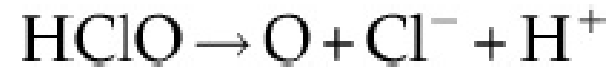
In neutral and basic media hydroxide ions generated at the cathode reacts with hypochlorous acid neutralizing it and generating hypochlorite ions



- Active forms of **chlorines** are efficient for disinfection of water containing *bacteria, viruses, fungi, and spores*. For example, *Candida albicans* fungi die within 30 seconds while exposed to 5% NaOCl solution.
- It is worth noting that not only is *hypochlorous acid* endowed with higher oxidizing power, but it also behaves as a *stronger disinfectant than hypochlorite*.
- In fact, with the cell wall of pathogenic microorganisms being naturally negatively charged, it can be entered more easily by the neutral hypochlorous acid than the negatively charged hypochlorite ion

- The superior disinfecting power of electrochlorination with respect to chemical chlorination can be explained by considering that, during the electrolysis, a number of different oxidants (i.e., hydroxyl radical, hydrogen peroxide, ozone) can be easily electrogenerated by water discharge at the anode.
- Anodes used for the process of electrodisinfection by hypochlorite ions should have **low overpotential toward chlorine gas evolution such as Pt**. However, pure Pt anodes are not used in industrial applications because of their high costs.
- Traditional electrodes for  $\text{Cl}_2$  gas evolution are  **$\text{PbO}_2$**  and **MMO (mixed metal oxide)** electrodes.

- Different concomitant effects, such as irreversible permeabilization of the cytoplasmic membrane caused by the electrical field, led to cell lysis by reaction of the biopolymers with electrogenerated oxidants, a release of highly reactive atomic oxygen thus contributing to effectively inactivating a broad range of microorganisms



- A paper also reports the removal of *Staphylococcus aureus* by active ruthenium-based electrodes in the absence of chloride Only a few species such as *Giardia* and *Cryptosporidium* are known to be chlorination resistant

- An issue of serious concern related to electrochlorination is the occurrence of side reactions leading to the formation of hazardous by-products. Although **trihalomethanes (THMs)** and **haloacetic acids (HAAs)** are considered as the main DBPs, hundreds of different chemicals have been identified *in treated drinking water*; for many of them, mutagenic or carcinogenic behavior has been verified.
- The World Health Organization (WHO) recommends very low concentrations of  **$\text{ClO}_3^-$**  and  **$\text{ClO}_4^-$**  in drinking water. A correct choice of anode material and operative conditions are key parameters to obtain a powerful mixture of disinfectant, limiting the production of DPBs.
- Despite concerns raised by toxic by-product formation along with unpleasant odor and taste, active chlorine remains hardly replaceable due to its high reactivity and relatively low-cost production and mostly for its capacity to provide a long-term biocidal action.

TABLE 4.1.3 Oxidation States of Chlorine

Oxidation number	Examples	
-1	Chloride ion	$\text{Cl}^-$
0	Elemental chlorine	$\text{Cl}_2$
1	Hypochlorous acid/Hypochlorite	$\text{HClO}/\text{OCl}^-$
	Chlorine oxide	$\text{Cl}_2\text{O}$
3	Chlorous acid/Chlorite	$\text{HClO}_2/\text{ClO}_2^-$
4	Chlorine dioxide	$\text{ClO}_2$
5	Chlorate	$\text{ClO}_3^-$
6	Chlorine trioxide	$\text{ClO}_3$
7	Perchlorate	$\text{ClO}_4^-$
	Chlorine heptoxide	$\text{Cl}_2\text{O}_7$
8	Chlorine tetroxide	$\text{ClO}_4$



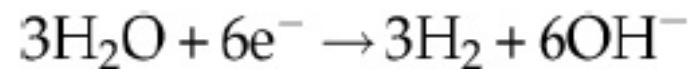
# Ferrate, $[\text{FeO}_4]^{2-}$

- An emerging oxidant that is stirring great interest is Ferrate  $[\text{FeO}_4]^{2-}$ , an anion containing iron at its highest oxidation state (IV) whose use has long been limited by the difficulty of preparation.
- Ferrate behaves as a powerfully strong oxidant at acidic pH ( $E^0 = + 2.20 \text{ V}$ ) while it shows a milder oxidizing ability under alkaline conditions ( $E^0 = + 0.72 \text{ V}$ ).
- Electrochemical synthesis of ferrate requires electrolysis with a *sacrificial iron-based anode* in a NaOH or KOH-rich electrolyte.
- The process performance mostly depends on anode material, applied current density, and electrolytes. The reactions involved are:

- at the anode



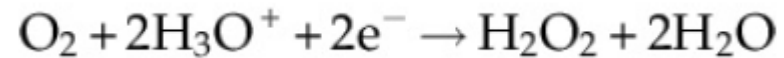
- at the cathode



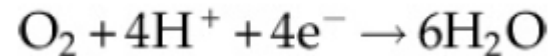
- Anode materials generally consist of iron, carbon steel, or cast iron.
- Porosity and composition of electrodes greatly affect the ferrate electrogeneration.
- Outstanding performance of ferrate (VI) relies on its multifunctional action:
  - i. it can inactivate a variety of microorganisms including some viruses while oxidizing a wide range of compounds (including emerging contaminants);
  - ii. moreover, due to the release of ferric ions, it also provides coagulant action. For example, Jiang et al., indicate that 0.5 mg/L of ferrate (VI) is sufficient to oxidize many chemicals and to achieve complete disinfection, with the performance unaffected by the initial content of the microbial load.

# Electrodisinfection with hydrogen peroxide

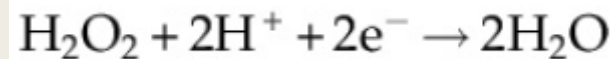
- This is the case of hydrogen peroxide, whose on-site production occurs via a reduction of the dissolved oxygen at carbon-based electrodes.
- The electrochemical route involves several reactions with formation of different radical species such as superoxide radicals  $O_2 \bullet^-$  and hydroperoxide radicals  $HOO\bullet$  with the following overall reaction:



- Major side reactions



- The decomposition of hydrogen peroxide



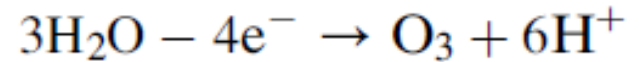
- and hydrogen gas evolution



- In a membrane-free reactor, the occurrence of an anodic oxidation and reaction with the species anodically generated (especially active chlorine), as well as reactions with species cathodically generated ( $O_2^-$ ,  $\bullet OH$ ,  $O_2H\bullet$ ) and decomposition at the cathode, seriously affect the production yields, preventing hydrogen peroxide from accumulating in aquaculture and swimming pools.
- Of note, decomposition of hydrogen peroxide forms water and oxygen as unique compounds, thus producing one of the least environmental impacts among all the known oxidants.
- However, the reactivity of hydrogen peroxide does not allow provision of the long-term effect required by current legislation.

# Electrodisinfection by ozone

- Ozone can be allocated at the anode having high overvoltage toward OERs, for example, BDD electrodes. Electrode reaction of O<sub>3</sub> anodic generation is described as follows:



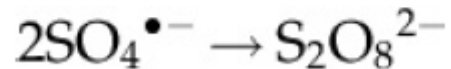
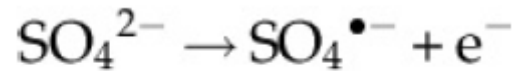
- Bactericidal effect of ozone is associated with its high oxidation potential (2.076 V) and the ease of diffusion through the cell walls of microorganisms. For example, polio virus dies within 2 min when ozone dosage is equal to 0.45 mg/L, while chlorine kills the virus only after 3 h with a dosage of 2 mg/L.
- Because both ozone and chlorine species are highly corrosive, corrosion resistant materials should be used for the construction of equipment and pipelines.

# Electrodisinfection by silver

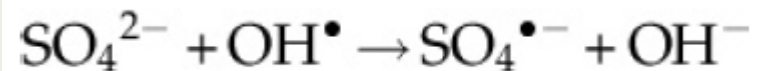
- Along with oxygen, ozone, and chlorine species, silver ions have high-antibacterial properties toward Staphylococcus, Streptococcus, typhoid, dysentery, and coliform bacteria.
- There are few hypotheses explaining the mechanism of silver-antibacterial properties. One of the mechanisms states that silver interacts with bacterial cell enzymes and violate cell exchange with the environment thus killing it. Another mechanism claims that silver ions penetrate the cell and bind with cell's protoplasts thus killing it. It is also suggested that silver adsorbs on the surface of cells and catalyzes reactions of cell plasma oxidation by oxygen.
- Anodic dissolution of silver anodes occurs by the following mechanism:
- $\text{Ag}^0 + e \rightarrow \text{Ag}^+$

# Electrodisinfection peroxydisulfate ion $S_2O_8^{2-}$

- While  $H_2O_2$  (hydrogen peroxide) and  $Cl_2$  (chlorine) are commonly used disinfectants in water treatment,  $S_2O_8^{2-}$  is a chemical oxidant that has been primarily used for aquifer remediation.
- The standard reduction potential for  $S_2O_8^{2-}$  is  $E^o = 2.01$  V. This  $E^o$  value is greater than that for  $H_2O_2$  ( $E^o = 1.8$  V) and  $Cl_2$  ( $E^o = 1.48$  V).
- A recent study has also shown that  $S_2O_8^{2-}$  is an efficient disinfectant against the bacterial species *Escherichia coli* and *Enterococcus faecalis*. The  $Cl\cdot$ ,  $ClOH\cdot^-$ , and  $SO_4^{\cdot-}$  species have also been shown to be active oxidants for contaminant destruction.



- The  $SO_4^{\cdot-}$  anion can also react with  $OH\cdot$



# Challenges Associated With Electrooxidation

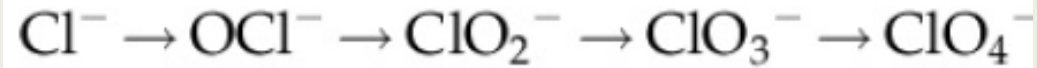
- The formation of halogenated byproducts is a concern when using electrochemical oxidation for water and wastewater treatment. Byproducts include halogenated oxyanions (e.g.,  $\text{ClO}_3^-$ ,  $\text{ClO}_4^-$ ,  $\text{BrO}_3^-$ ) and a wide variety of halogenated organic compounds.



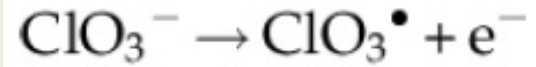
# Inorganic Byproduct Formation

- The formation of halogenated oxyanions, including  $\text{ClO}_3^-$ ,  $\text{ClO}_4^-$ , and  $\text{BrO}_3^-$ , has been detected in numerous studies. Of these oxyanions,  $\text{ClO}_4^-$  is especially problematic because it is a terminal oxidation product, its consumption has been linked to adverse health risks, and  $\text{Cl}^-$  is ubiquitous in natural and wastewater streams, making it especially challenging to control its formation.
- The EPA has issued a health advisory level for  $\text{ClO}_4^-$  of 15  $\mu\text{g}/\text{L}$  for drinking water sources, and Massachusetts and California have set even lower drinking water standards of 2 and 6  $\mu\text{g}/\text{L}$ , respectively.

- The formation of  $\text{ClO}_4^-$  is via a stepwise oxidation pathway starting from  $\text{Cl}^-$ , as shown



- The rate-determining step for the formation of is the oxidation of  $\text{ClO}_3^-$  to  $\text{ClO}_4^-$ . The conversion of  $\text{ClO}_3^-$  to  $\text{ClO}_4^-$  on BDD anodes has been shown to be a two step process. The first step is a direct electron transfer reaction of  $\text{ClO}_3^-$  at the electrode surface

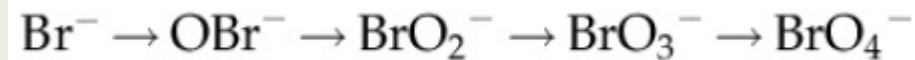


- The second step is the homogeneous reaction between  $\text{ClO}_3^-$  and  $\text{OH}^\bullet$  to form  $\text{HClO}_4$



- It was shown that formation on BDD electrodes is approximately 50–100 times higher than on Pt and mixed-metal oxide electrodes. These results are likely due to the fact that  $\text{OH}^\bullet$  is not formed at high quantities on these active electrode materials.

- The formation of  $\text{BrO}_3^-$  during electrochemical oxidation is also of concern, as the EPA has set a maximum contaminant level (MCL) of 0.01 mg/L for drinking water. The  $\text{Br}^-$  content of natural waters is often at least an order of magnitude lower than  $\text{Cl}^-$ , but  $\text{BrO}_3^-$  formation has been shown in numerous electrochemical studies.
- In some cases,  $\text{BrO}_3^-$  was further oxidized to  $\text{BrO}_4^-$ . There have not been any mechanistic studies that focused on the electrochemical formation of  $\text{BrO}_3^-$  and  $\text{BrO}_4^-$ . However, initial studies have suggested that the formation of  $\text{BrO}_x^-$  species follows a stepwise pathway, which is similar to  $\text{ClO}_x^-$  formation.



- $\text{BrO}_3^-$  accumulates in solution and slowly oxidizes to  $\text{BrO}_4^-$ , which suggests the rate determining step for  $\text{BrO}_4^-$  formation is the oxidation of  $\text{BrO}_3^-$ .

# Halogenated Organic Compound Formation

- The formation of halogenated-organic compounds (HOCs) has been detected during the application of EAOPs to a variety of solution conditions.
- HOC formation is attributed to addition and substitution reactions between organic compounds and in situ formed halogenated oxidants. These oxidants include active chlorine (e.g.,  $\text{Cl}_2$ ,  $\text{OCl}^-$ ,  $\text{HOCl}/\text{OCl}^-$ ) and bromine (e.g.,  $\text{Br}_2$ ,  $\text{OBr}^-$ ,  $\text{HOBr}/\text{OBr}^-$ ) species, chlorine radicals ( $\text{Cl}\cdot$ ,  $\text{Cl}_2\cdot^-$ ), and bromine radicals ( $\text{Br}\cdot$ ,  $\text{Br}_2\cdot^-$ ).
- Studies indicated that
  - (1) HOCs were continuously formed during electrolysis while halogens and organics were both present,
  - (2) HOCs were completely oxidized to inorganic end products (i.e.,  $\text{CO}_2$ ,  $\text{ClO}_3^-$ ,  $\text{ClO}_4^-$ ,  $\text{BrO}_3^-$ ,  $\text{BrO}_4^-$ ) after elimination of halogen ions or halogenated oxidants, and
  - (3) the incorporation of halogens into organic compounds increased in the following order:  $\text{Cl} < \text{I} < \text{Br}$ .

**TABLE 2.2 Removal Efficiency of Organic Pollutants From Water at Different Anodes**

Targeted Pollutant	Anode Type	Working Parameters	Removal Efficiency	Reference
<b>Organic Compounds</b>				
Reactive Blue 109 (1000 mg/L)	Pt	NaCl (0.1 M) $j = 20 \text{ mA/cm}^2$ pH 4 $t = 1.25 \text{ h}$	96% COD	[6]
Dimethyl phthalate (0.03 mM)		$\text{Na}_2\text{SO}_4$ (0.2 M) $j = 20 \text{ mA/cm}^2$ pH 7 $t = 18 \text{ h}$	20% 10% COD	[27]
Diethyl phthalate (0.03 mM)		$\text{Na}_2\text{SO}_4$ (0.2 M) $j = 20 \text{ mA/cm}^2$ pH 7 $t = 18 \text{ h}$	50% 30% COD	
Diheptyl phthalate (0.03 mM)		$\text{Na}_2\text{SO}_4$ (0.2 M) $j = 20 \text{ mA/cm}^2$ pH 7 $t = 18 \text{ h}$	100% 100% COD	
Phenol (490 mg/L)		$\text{Na}_2\text{SO}_4$ (0.25 M) $t = 20 \text{ h}$ $j = 20 \text{ mA/cm}^2$ pH 5	100% 20% TOC	[28]

Methylene blue (40 mg/L)	Pt/MnO <sub>2</sub>	Na <sub>2</sub> SO <sub>4</sub> (0.05 M) j = 7 mA/cm <sup>2</sup> pH 8 t = 2 h	90% 70% COD	[29]
Landfill leachate (COD 1414 mg/L)	Graphite carbon electrode	Na <sub>2</sub> SO <sub>4</sub> (1 g/L) j = 79 mA/cm <sup>2</sup> t = 4 h	68% COD 84% color	[30]
Amoxicillin (19.6 mg/L TOC)	Ti/Ti <sub>4</sub> O <sub>7</sub>	Na <sub>2</sub> SO <sub>4</sub> (0.05 M) j = 5 mA/cm <sup>2</sup> t = 8 h	69% TOC	[31]
Phenol (100 mg/L)	Ti/SnO <sub>2</sub> -Sb-Mo	Na <sub>2</sub> SO <sub>4</sub> (0.25 M) j = 10 mA/cm <sup>2</sup> t = 3.5 h	99.6% 82.7% TOC	[32]
Aniline (2.7 mM)	PbO <sub>2</sub>	pH 2 I = 2 A t = 1 h	>90%	[33]
Sanitary landfill leachate (COD 6.2 g/L)	Ti/Pt/PbO <sub>2</sub>	I = 0.3 A t = 6 h	40% COD	[34]
Sanitary landfill leachate (COD 6.2 g/L)	Ti/Pt/SnO <sub>2</sub> -Sb <sub>2</sub> O <sub>4</sub>	I = 0.3 A t = 6 h	40% COD	[34]
4-chlorophenol (100 mg/L)	Ti/IrO <sub>2</sub> -RuO <sub>2</sub>	Na <sub>2</sub> SO <sub>4</sub> (0.1 mM) j = 39 mA/cm <sup>2</sup> t = 2 h	100% >70% COD	[35]
Phenol (0.05 mM)	Ti-Ta <sub>2</sub> O <sub>5</sub> -IrO	KCl (0.01 M) t = 8 h E <sub>cell</sub> = 1.5 V pH 2, 7, 12	99%	[36]
	Ti/SnO-RuO <sub>2</sub> -IrO <sub>2</sub>			
	Ti/RhO <sub>2</sub> -IrO <sub>2</sub>			
Methylene blue (0.025 mM)	Ti-Ta <sub>2</sub> O <sub>5</sub> -SnO <sub>2</sub>	Na <sub>2</sub> SO <sub>4</sub> (0.1 M) j = 9.1 mA/cm <sup>2</sup> t = 3 h	38.6% TOC 95% color	[37]

**TABLE 2.2 Removal Efficiency of Organic Pollutants From Water at Different Anodes—cont'd**

Targeted Pollutant	Anode Type	Working Parameters	Removal Efficiency	Reference
Phenol (100 mg/L)	BDD	Na <sub>2</sub> SO <sub>4</sub> (0.25 M) j = 10 mA/cm <sup>2</sup> t = 6 h	100% 95.4% TOC	[42]
Sanitary landfill leachate (COD 6.2 g/L)		I = 0.3 A t = 6 h	40% COD	[34]
Dimethyl phthalate (0.03 mM)		Na <sub>2</sub> SO <sub>4</sub> (0.2 M) j = 20 mA/cm <sup>2</sup> pH 7 t = 0.5 h	100% 50% COD	[27]
Diethyl phthalate (0.03 mM)		Na <sub>2</sub> SO <sub>4</sub> (0.2 M) j = 20 mA/cm <sup>2</sup> pH 7 t = 0.5 h	100% 50% COD	[27]
Diheptyl phthalate (0.03 mM)		Na <sub>2</sub> SO <sub>4</sub> (0.2 M) j = 20 mA/cm <sup>2</sup> pH 7 t = 0.5 h	50% 10% COD	[27]
Amoxicillin (19.6 mg/L TOC)		Na <sub>2</sub> SO <sub>4</sub> (0.05 M) j = 5 mA/cm <sup>2</sup> t = 8 h	36% TOC	[31]
Aniline (500 mg/L)		Ti/TiO <sub>x</sub> H <sub>y</sub> /Sb–SnO <sub>2</sub>	Na <sub>2</sub> SO <sub>4</sub> (5 wt.%) j = 20 mA/cm <sup>2</sup> t = 5 h	85% 71% COD

Inorganic Compounds					
Na <sub>2</sub> S (0.023 M)	Ti/RuO <sub>2</sub>	j = 25 mA/cm <sup>2</sup> pH 13 t = 5 h	100%	[51]	
Na <sub>2</sub> S (60 mM)	BDD	j = 33 mA/cm <sup>2</sup> t = 5h NaCl 1%	100%	[52]	
Na <sub>2</sub> S (30 mM)	Ti/IrO <sub>2</sub> -Ta <sub>2</sub> O <sub>5</sub>	j = 13.5 mA/cm <sup>2</sup> t = 6 h NaOH (0.25 M)	83%	[53]	
Thiocyanate, SCN <sup>-</sup> , (852.2 mg/L)	Ti/Ru <sub>0.3</sub> Ti <sub>0.7</sub> O <sub>2</sub>	E = 8 V pH 9 t = 6 h NaCl 0.01M	90%	[54]	
Cyanides (CN <sup>-</sup> ) including thiocyanate (SCN <sup>-</sup> ) (280 mg/L)	PbO <sub>2</sub>	j = 6.7 mA/cm <sup>2</sup> pH 4 NaCl 1 g/L	99.6%	[55]	
NaCN (250 mg/L)	Ti/SnO <sub>2</sub> -Sb-Ce	j = 30 mA/cm <sup>2</sup> pH 13 t = 4 h	98.2%	[56]	



## Electrochemical Disinfection

Toilet wastewater <i>Escherichia coli</i> <i>Enterococcus</i>	Bismuth-doped TiO <sub>2</sub>	E = 4 V pH 6.7–8.3 t = 10 min	5-log <sub>10</sub> reduction	[57]
<i>Artemia salina</i>	Si/BDD	j = 255 mA/cm <sup>2</sup> NaCl 3 g/L t = 1 h	100%	[58]
<i>Pseudomonas aeruginosa</i>	BDD	j = 167 mA/cm <sup>2</sup> t = 5 min NaCl 20 mg/L	6-log <sub>10</sub> reduction	[59]
<i>Escherichia coli</i>	PbO <sub>2</sub> /graphite	j = 253 mA/cm <sup>2</sup> NaCl 20 mg/L	100% (8 min)	[60]
<i>Enterococcus faecalis</i>			100% (60 min)	
<i>Artemia salina</i>			100% (40 min)	

BDD, boron-doped diamond; COD, chemical oxygen demand; E, applied voltage at electrolysis (V); I, applied current (A); j, applied current density; t, electrolysis time (h).