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Mechanistic insight into disinfection by electrocoagulation—A review

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ABSTRACT

To protect environmental and human health, enhanced treatment methods are more than required to kill microorganisms from wastewater. The electrocoagulation (EC) process is more and more employed to remedy wastewater. This review aims to focus on the EC process as an electrodisinfection (ED) technique, i.e., a microorganism killing method, in terms of the mechanisms involved. An excellent performance of EC is shown through a large review of literature. The electric field (EF) contribution remains fundamental in killing microorganisms. Also, the adsorption or cohesion of bacteria onto Fe/Al hydroxides is considered a key stage in ED upon EC. Much more effort needs to be performed to qualitatively and quantitatively decide between EF and cohesion contributions. More research should be addressed to assessing more and more probable generation of the hydroxyl radical ($^{\bullet}$OH) through the EC process.

Keywords: Electrocoagulation (EC); Electrodisinfection (ED); Electric field (EF); Electro-Fenton (E-F); Boron-doped diamond (BDD); Stainless steel (SS); Advanced oxidation process (AOP); Reactive oxygen species (ROSs); Reactive chlorine species (RCSs)

1. Introduction

Since the famous Vik et al.'s work in 1984 [1] on electrocoagulation (EC) of potable water, a huge amount of researches has been published on applying EC as an electrochemical wastewater technique. Since our well-known work [2] on the application of EC in *Escherichia coli* (*E. coli*) culture and two surface waters, a considerable number of studies has been released on implementing EC as an electrochemical disinfection (or electrodisinfection (ED)) method. In our recent publication [3], a special focus was put on microorganisms' ED phenomena generally. In the present review, attention is paid to the processes involved in killing microorganisms through the EC technology specifically. Between our two articles mentioned above, in our review [4], we have opened a scientific and technological discussion about the promising transition from the chemical disinfection to ED. Later in our review [5], we have attracted the scientific community's focus on the fact that the large application of the ED approaches risks to be inhibited by several technological difficulties like chlorine by-product formed species. In point of fact, through electrochemical technique, such carcinogenic substances may be generated following the electrode material and applied voltage. We deduced that the employment of electrodes forming highly reactive species should be more cautiously restrained in hygienically and environmentally directed usages.

To remain focused on the EC process, we attracted the attention of the advanced oxidation process (AOP) in the EC technique [6]. AOPs have been largely described as near ambient temperature treatment processes based on highly reactive radicals, especially the hydroxyl radical ($^{\bullet}$OH) as the main oxidant. In theory, as water-containing colloidal particulates, oils, or other pollutants, pass inside the applied electric field (EF) [2], there may be ionization, electrolysis, hydrolysis, and free-radical generation which may

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modify the physicochemical features of water and pollutants. In addition, if the electrochemical reactors function at an elevated cell potential and an anodic phenomenon happens in the potential region of water discharge, hydroxyl radicals ($^{\bullet}OH$) are produced. With a view to having more probabilities of having free radicals generation during EC, ultrasound through EC may be very helpful [6]. Ultrasound using the EC process is discussed in [6]. Free radicals are generated in cavitation; a release of gas at the electrodes intensifies the processes of their contribution in flocculation [6]. Moreover, the EC process at a pH less of than 3 possesses more probability to form hydroxyl radicals. Recently, Medel et al. [7] worked on the same research axis suggested five years ago.

This review aims to focus on the EC process as an ED technique, i.e., a killing microorganisms' method, in terms of the mechanisms involved.

2. Electrodisinfection (ED)

Removing pathogenic microorganisms, suspended or as attached biofilms, is a fundamental stage in treating water from various sources [8,9], like raw water supply [10], ballast water [11,12], drinking water reservoirs and water distribution systems [13–15], process wash water in food processing plants [16,17], brackish or industrial briny waters for use in food industry [18], swimming pools and drinking water [19–24], etc. This is frequently performed upon injecting chemical products like chlorine, chlorine dioxide and ozone [25–29]. The most usual technique, chlorination, is linked with many issues like transport and storage of chlorine [30–34], formation of toxic by-products like trihalomethanes, haloacetic acids, and N-nitrosodimethylamine [5,35–39], and the resistance of several pathogens comprising pathogenic *Escherichia coli* (*E. coli*) and *Campylobacter jejuni* (*C. jejuni*) bacteria, enteric viruses like rotavirus and calicivirus, and the parasites *Cryptosporidium* and *Giardia lamblia* (Table 1) [38,40].

ED has attracted a special focus as a promising option to classical chlorination [16,41] because of its environmental compatibility, simple installation and operation, and effectiveness for inactivation of a large set of microorganisms from bacteria to viruses and algae under mild pressures and temperature [27,42–47]. It has been established that electrochemical technique can assure elevated killing microorganisms' performance for potable water [48,49], raw water supply [20], liquid foodstuff [50], and industrial and domestic wastewater effluents [51,52]. The application of treating water upon imposing an electric voltage had been mentioned at the dawn of the nineteenth century; even so, this technique has only recently come into effective long-term implementation [43,53–57].

ED is relatively an environmentally friendly and strong technique with a two-stage mechanism of action (Table 2) [27,58–60].

During water treatment [61–67], the total concentration of dissolved chlorine following the chlorination operation is known as active chlorine, and is calculated by the addition of three species: free chlorine (Cl_2), hypochlorous acid (HClO) and hypochlorite ion (ClO^-). The mass distribution of these three main reactive chlorine species (RCSs) is a function of the pH of the medium [27,28].

Additional benefits of ED are the on-site production of disinfectants with governable injection [41,52] and comparatively low energy demand (Fig. 1) that enables the employment of environmentally friendly energy sources like solar cells or fuel cells [27,58,68,69]. In general, the elevated performance of ED is related to the interactive impacts of direct oxidation on the electrode surface [49,50], the formation of the reactive intermediate species like ROS or RCS with powerful bactericidal action [21,44,61], or the EF effect [2,3,50,70].

Choosing a convenient anode material remains a fundamental parameter in electrochemical methods, since it affects both the performance of the operation and the electrode selectivity [5,71,72]. Frequent anode materials employed in researches of water ED are titanium with active coatings based on metal oxides,which are known as Dimensionally Stable Anodes (DSA®s) [38], platinum [41] and boron-doped diamond (BDD) electrodes [12,46,73,74]. DSA® type electrode materials comprise IrO_2-RuO_2 [28], TiO_2-RuO_2 [38], SnO_2 [75], and IrO_2-Sb_2O_5-SnO_2 [76]. Such

Table 1
Mainwater borne pathogens [14]

Waterborne pathogens classifications	
Bacteria	
Description	Unicellular microorganisms, free living or parasitic
Important pathogens	*B. pseudomallei, C. jejuni/, E. coli O157:H7, Legionella* spp.*, Leptospira, Salmonella* spp. (*s. typhi*), *Shigella* spp., *V. cholerae, Y. entercolitica*
Frequent health problems	Typhoid & paratyphoid fever, dysentery, cholera, diarrhea, nausea
Viruses	
Description	Obligate, intracellular parasites, most-commonly enteric viruses
Important pathogens	Adenovirus, astrovirus, enterovirus, hepatitis A&E, Norwalk virus, reovirus, rotavirus
Frequent health problems	Jaundice and fever (hepatitis A&E), vomiting, diarrhea
Protozoa	
Description	Single-cell organisms, intestinal parasites that form (oo) cysts
Important pathogens	*Acanthamoeba* spp., *Cryptosporidium parvum, C. cayetanensis, E. histolytica, Giardia lamblia*
Frequent health problems	Diarrhea and dysentery, giardiasis

Table 2
ED two-stage mechanism of action [27]

ED two-stage mechanism	
Stage 1 *Direct oxidation (at the electrode surface)*	This stage is characterized by the instantaneous killing of microbial cells [41] which is caused by the direct electron transfer reaction after the electro-sorption at the electrode surface [41].
Stage 2 *Indirect oxidation (in the bulk solution)*	This stage is well-known by the generation of (1) killing species from water oxidation, like hydroxyl radical ($^{\bullet}OH$), atomic oxygen ($^{\bullet}O$), hydrogen peroxide (H_2O_2), and ozone (O_3) (Eqs. (1)–(5)) [22,61–63] considered as reactive oxygen species (ROSs), or of (2) oxidants formed from the substances dissolved in water, like chloride is oxidized to free chlorine, according to Eq. (6) [51,54,64,65]: $H_2O \rightarrow {}^{\bullet}OH + H^+ + e^-$ (1) ${}^{\bullet}OH \rightarrow {}^{\bullet}O + H^+ + e^-$ (2) $2{}^{\bullet}O \rightarrow O_2$ (3) $2{}^{\bullet}OH \rightarrow H_2O_2$ (4) $O_2 + {}^{\bullet}O \rightarrow O_3$ (5) $2Cl^- \rightarrow Cl_2 + 2e^-$ (6) Then, dissolved chlorine is hydrolyzed to hypochlorous acid/hypochlorite ion and hydrochloric acid, in main side reactions of anodic production of chlorine, as given in Eqs. (7) and (8): $Cl_2 + H_2O \rightarrow Cl^- + HClO + H^+$ (7) $HClO \rightarrow ClO^- + H^+$ (8)

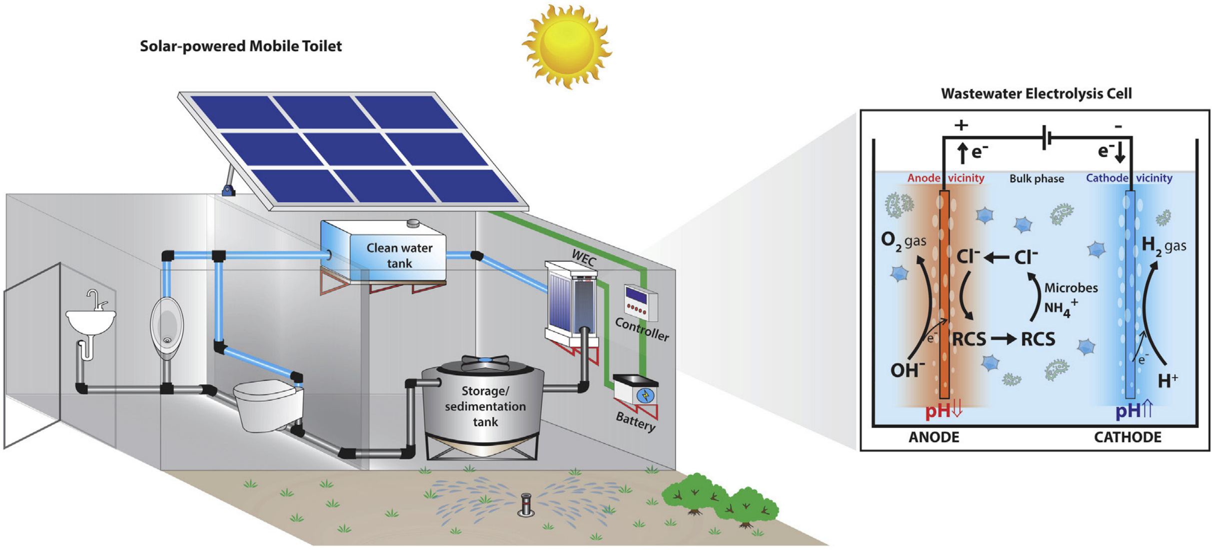

Fig. 1. Schematic of a solar-powered mobile toilet using wastewater electrolysis cells for toilet wastewater treatment [52].

electrodes have demonstrated more elevated performances in the generation of free chlorine relatively to Pt and diamond electrodes; this fact is of crucial significance in real uses of electrochemical methods in the presence of chloride salts [54,77]. Moreover, diamond electrodes may then oxidize hypochlorite to chlorate and perchlorate [78] which are allowable in potable water only at very low levels [54]. Consequently, DSA® type electrodes are more employable in the ED of water because of their more elevated performance in the generation of oxidizing species [27,79].

The stages involved in the electrochemical killing of microorganisms are not totally comprehended [27]. Mainly, the vital physiological functions of bacteria are programmed into the cell membrane, cytoplasm, and nucleic acids (DNA and RNA). Therefore, harm to any of such subcellular components of bacteria may cause the deactivation of the bacteria. Researchers [44] detected infiltration of vital intracellular materials from *E. coli* cells following an electrochemical application by DSA®s upon scanning electron microscope. Other scientists [80] noticed modifications in the internal constituents and cell walls of *E. coli* as a consequence of BDD treatment. Tanaka et al. [81] showed lipid peroxidation in the cell membranes of disinfected bacteria by electrochemical mean in seawater using a Pt anode. Long et al. [46] examined the subcellular mechanisms of *E. coli* deactivation through BDD electrochemical disinfection in three electrolytes: in chloride solution, *E. coli* deactivation was affected by deterioration of the intracellular enzymatic systems; in sulfate solution, the removal of some vital membrane proteins like K^+ ion transport systems fundamentally caused cell deactivation; and in phosphate solution, mineralization of their intracellular organic constituent was in charge of cell deactivation [27].

Shang et al. [82] mentioned a performant electrochemical treatment for potable water disinfection employing a pyrolytic graphite electrode modified with ferrocenyl tetheredpoly (amidoamine) dendrimers–multiwalled carbon nanotubes–chitosan nanocomposite. They studied the effects of parameters of ED of *E. coli* and *Staphylococcus aureus*, like applied potential and sterilization period. They found that almost all (99.99 %) of the initial bacteria were inactivated after applying a low potential of 0.4 V for 10 min. Through the ED operation, the oxidized form of ferrocene was produced on electrode, which played a fundamental role in the disinfection towards *E. coli* and *S. aureus*.

Bruguera-Casamada et al. [83] examined the disinfection of 100 mL of synthetic water containing 7 mM Na_2SO_4 with 10^6 colony forming units (CFU)/mL of either Gram-negative or Gram-positive bacteria using electrochemical oxidation. Their electrolytic cell was a stirred tank reactor equipped with a BDD anode and a stainless steel (SS) cathode and the tests were realized at acidic and neutral pH, at 33.3 mA/cm^2 and 25°C. ROSs, mostly hydroxyl radicals, were formed in both media from water oxidation at the BDD anode and the bacteria amount was decreased by ≥5 log units after 60 min of electrochemical treatment, therefore constituting a good chlorine-free disinfection operation. The ED with BDD was very efficient for Gram-negative bacilli such as *E. coli* and *Pseudomonas aeruginosa* and Gram-positive ones such as *Bacillus atrophaeus*, while the Gram-positive cocci *Staphylococcus aureus* and *Enterococcus hirae* were more resistant. Consequently, the latter microorganisms may be considered as a better choice than *E. coli* as process indicators. Scanning electron microscopy (SEM) (Fig. 2) underlined a transition from initial cells with standard morphology supported on clean filters to deactivated cells with a greatly modified morphology lying on dirty filters with plenty of cellular debris. More serious harm was noticed for Gram-negative cells compared with Gram-positive ones. The deactivation impact may thus be linked to the chemical composition of the outer layers of the cell structure along with the change of the transmembrane potentials upon current passage.

3. Electrocoagulation

Through electrocoagulation (EC) [84–88], electric current is passed across a sacrificial anode to dissolve *in situ* coagulant precursor cations (Fig. 3); these cations hydrolyze quickly to generate dissolved hydroxyl complexes and insoluble hydroxide precipitates [89–93]. Over electrolysis, gas exsolution may conduct to floc-flotation, which is known as electroflotation (EFL) if the anode is inert [94,95], when the floating layer is skimmed and only the remaining non-floating colloids present in the water column are sent downstream for additional liquid-solid separation [96–103]. The expanding attention in implementing electrolytic methods, such as EC, can be linked to their (i) convenience for utilization in pre-engineered transportable packaged factories, (ii) decreased employment of corrosive chemical products, (iii) accessibility of improved module arrangements, and (iv) success through a large collection of water chemistries (such as changing pH and alkalinity) [104–108].

More details about the EC process may be found elsewhere [109–113].

4. Electrocoagulation (EC) disinfection mechanisms

ED has been revealed employing carbon, mixed metal oxides, BDD, and other DSAs widely employing model waters not containing natural organic matter (NOM) [92]. The main benefit of simple electrochemical deactivation is that *in situ* disinfectant production decreases the hazard related to transport and on-site storage of big quantities of highly poisonous chemical products [5,114]. Killing microorganisms in such devices happens over the formation of oxidants (like chlorine) and free radical intermediates (like ROSs) [22,115]. On the other hand, as mentioned above, EC is carried outemploying sacrificial (not dimensionally stable) anodes and real-life surface waters carrying NOM. EC single is greatly effective for bacteria and algae removal [2,116–119].

It was proved that FeEC followed by microfiltration (MF) (EC/MF) was more efficient than chemical coagulation for virus elimination from synthetic water destitute of NOM reaching >4 log elimination at 10 mg Fe/L injection compared with only 2 log elimination at an equivalent ferric chloride injection [120]. Later, researchers such as Tanneru and Chellam [121] established that this tendency is reversed for surface water carrying 5 mg-C/L NOM where EC/MF only eliminated 1.5 log of MS2 viruses at 13 mg Fe/L, whereas 6.5 log elimination was evaluated from synthetic water at an identical Fe injection. The existence of 5 mg-C/L of Suwannee Riverhumic acid reduced virus elimination by roughly 4-log at pH 6.4 and approximately 2-log at pH 7.5 by EC/MF compared to $FeSO_4$ coagulation/MF [121]. Therefore, it was suggested that NOM exacerbated virus elimination through complexing anode dissolved Fe(II), hindering its oxidation to insoluble Fe(III) [92], and therefore decreasing coagulant precipitation and sweep flocculation [122]. On the other hand, researchers [123] mentioned that 3 mg-C/L of Suwannee River fulvic acid did not significantly affect *E. coli* reduction from synthetic groundwater. Therefore, the amount and constitution of NOM seem to have made crucial contributions to influencing microorganism elimination/deactivation in surface- and groundwaters. Moreover, viruses are deactivated by Fe(II) and Fe(0) (if no NOM is existent); however, the fundamental stages have not until now been unarguably established [124] even though present-day proof indicates oxidative stress [123,125]. It is confirmed that the initial advantageous findings on virus elimination upon iron EC/MF were achieved by employing synthetic waters without NOM [120]. It seems that contradictory publications concerning the NOM influences through iron EC for bacteria and viruses and between surface- and groundwa-

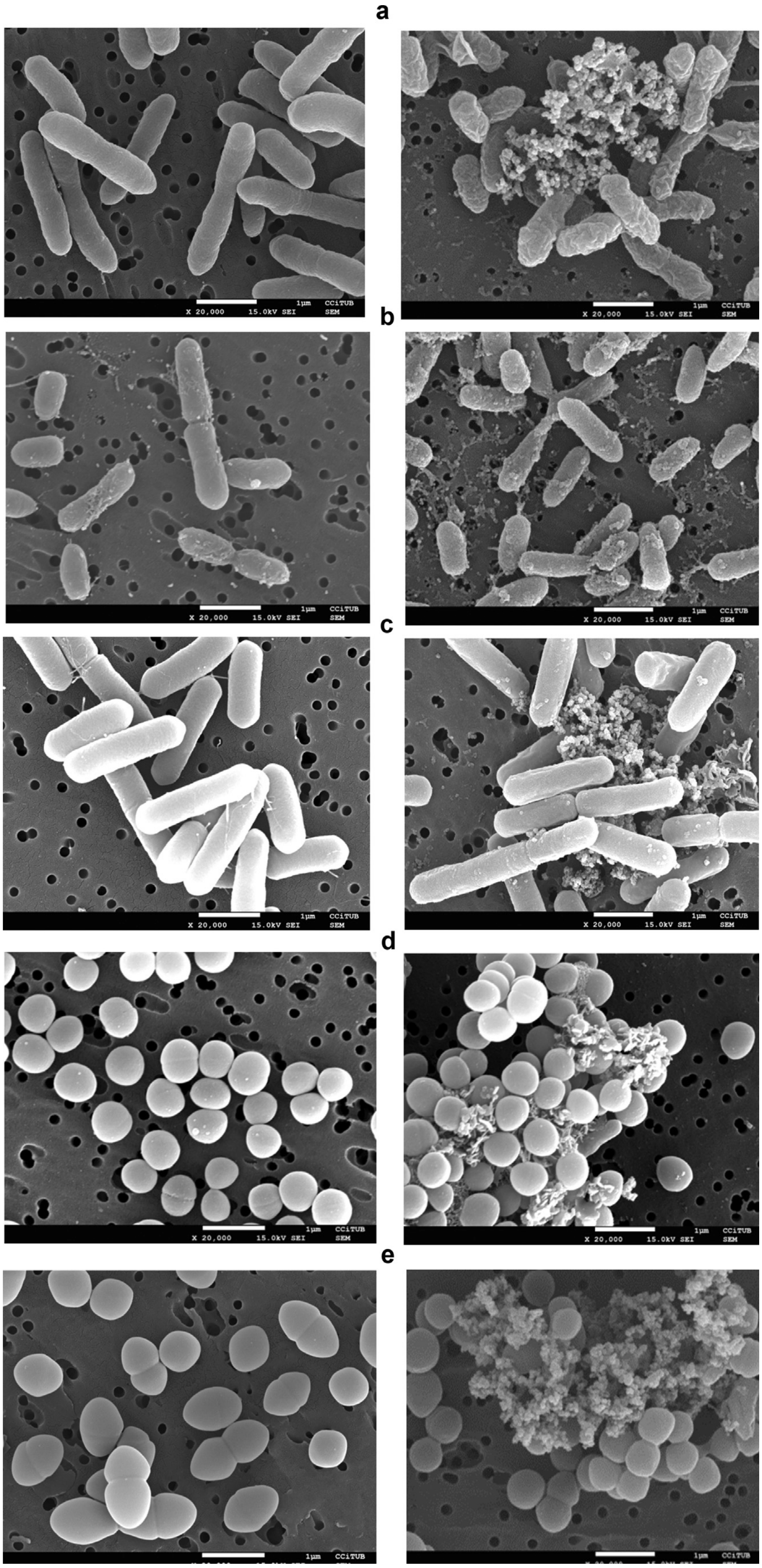

Fig. 2. SEM images for: (a) *E. coli* (b), *P. aeruginosa*, (c) *B. atrophaeus*, (d) *S. aureus* and (e) *E. hirae* supported on polycarbonate membrane filters. Samples correspond to bacteria suspensions in 7 mM Na_2SO_4 at pH 7.0, before (left) and after (right) 45 min of electrochemical oxidation treatment with a BDD/SS cell at 33.3 mA/cm^2 and 25°C [83].

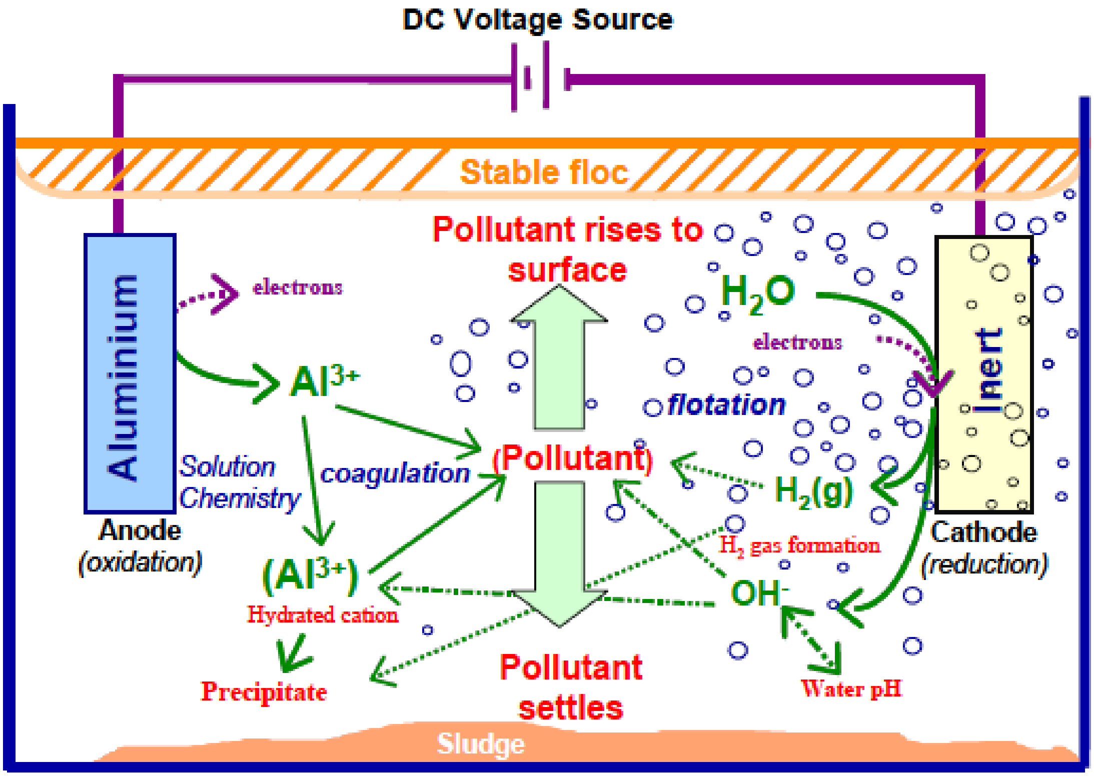

Fig. 3. Mutual actions happening inside EC reactor [86].

ter [121,123] establish the necessity for additional studies to consistently estimate the action of NOM on the efficiency of iron EC/MF for treating NOM-laden surface waters.

Pathogenic viruses fixed by flocs produced by classical alum coagulation and aluminum EC of surface water have been recuperated upon dissolving them at elevated pH employing beef extract (but not for polyaluminum chloride) [92,126,127]. Consequently, different from Fe [128], Al electrolysis does not deactivate viruses upon low-salinity situations typical of natural water. However, Al is more performant than Fe in eliminating viruses from NOM-containing surface waters (see Fig. 4) because of effective $Al(OH)_{3(s)}$ precipitation and enmeshment while Fe did not significantly precipitate following electrolysis upon these situations [121,129].

Understanding of the virus-floc interactions has been reached through atomic force microscopy using tips with covalently immobilized viruses (see inset in Fig. 4b) [129]. Unbinding force evaluated from pull-off curves corresponding to the vertical retraction of virus-coated tips from the floc interface in a liquid cell is illustrated in Fig. 4b for 0, 2, 5, and 20 mgAl/L injections. For the raw water and the lowest injection tested (2 mg/L), there were minor mutual actions between the tip and the flocs conducting to law reductions by EC. More elevated injections enabled viruses to cohere-powerfully and numerous peaks were detected as the tip was retracted from the floc surface in the contact mode [92]. Several pull-off events correspond to mutual actions of capsid proteins of viruses on the tip with NOM, viruses, and $Al(OH)_3$ precipitates (comprising polyvalent cations bridges) as well as generation and breakage of intra-protein bonds as the virus is pulled [130]. Fluorescence microscopy as well has given visual proof for virus enmeshment during EC [129]. EFL of cyanobacteria by taking benefit of its favorable buoyancy (with no deactivation) has also been proved to be efficient for algae elimination [36,95,116,131,132].

Algae and virus removal is improved at elevated chloride ion concentrations because of chlorine-induced inactivation on top of physical elimination by coagulation [36,95,116,129,131,132]. This can be seen in Fig. 5, which illustrates reducing pathogenicity of the MS2 virus through electrolysis of synthetic water carrying elevated chloride ion amounts but lacking NOM (green and red curves). Under these situations, about 0.02 mg Cl_2/L was detected resulting in 1–1.5 log deactivation across the first hour. Nevertheless, shielding and aggregation inside flocs significantly slow down disinfection kinetics, achieving only 2 log deactivation after 5 h. Consequently, physical elimination controls deactivation for global microorganism removal during electrochemical treatment [133].Chlorine is as well supposed to react with any NOM that may be existent in natural water. Consequently, artificially prolonged flocculation/contact times would be required to attain important deactivation through Fe/Al EC of surface water [92].

In addition to being disinfectant precursors, chloride ions as well attack the passivation layer on sacrificial electrodes improving coagulant chemical dissolution because of pitting corrosion [92,134,135].

In addition, Anfruns-Estrada et al. [117] compared the capacity of two types of electrochemical technologies, i.e., EC and electro-Fenton (E-F), to disinfect primary and secondary effluents from municipal wastewater treatment plants (WWTPs). Heterotrophic bacteria, *E. coli*, enterococci, *Clostridium perfringens* spores, somatic coliphages and eukaryotes (amoebae, flagellates, ciliates and metazoa)

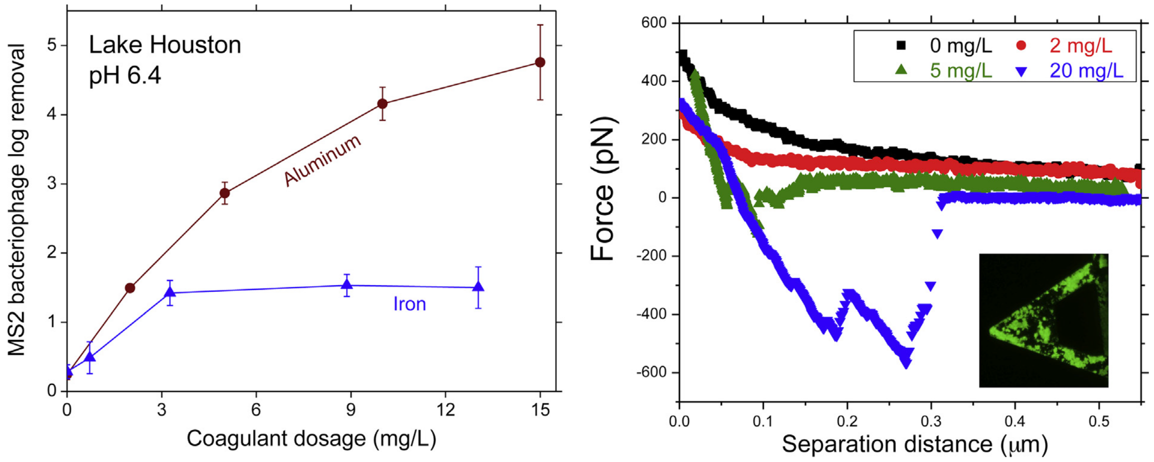

Fig. 4. Al EC eliminates viruses from surface water to a more important extent than Fe (left). AFM pull-off curves during for the retraction of virus-coated tips from the surfaces of Al(OH)$_3$ flocs formed during EC of lake Houston water. Fluorescent image of viruses bonded on Si$_3$N$_4$ tips using 3-aminopropyl-triethoxysilane (APTES) is shown in the inset on the right [92].

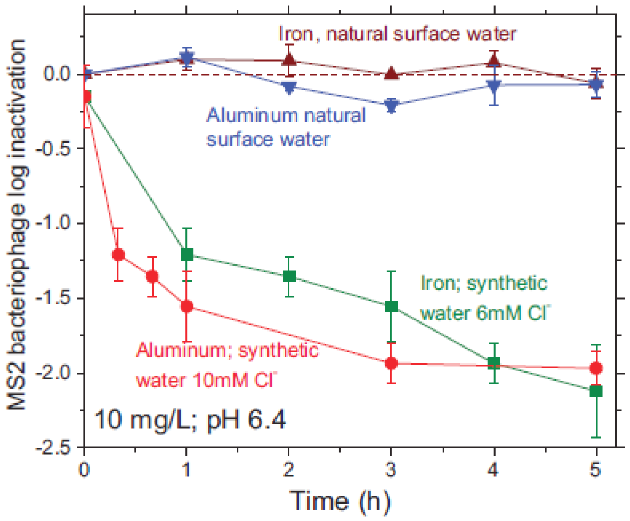

Fig. 5. Viruses are not deactivated through EC of NOM-laden surface water. The MS2 bacteriophage loses pathogenicity through EC of chloride-rich synthetic waters that do not carry NOM [92].

were examined as indicator microorganisms. EC with an Fe/Fe cell at 200 A/m^2 and natural pH permitted >5 log unit elimination of *E. coli* and final concentration below 1 bacteria/mL of coliphages and eukaryotes from both effluents in ca. 60 min, whereas heterotrophic bacteria, enterococci and spores were more resistant. A more significant elimination was reached for the primary effluent, likely because the flocs eliminate bigger quantity of total organic carbon (TOC), enmeshing more simply the microbiota. E-F with a BDD anode and an air-diffusion cathode that generates H_2O_2 on site was primarily realized at pH 3.0, with great or even total deactivation of microorganisms inside 30 min. A more performant microorganism elimination was obtained comparatively with EC because of $^{\bullet}$OH produced through Fenton's reaction. Faster disinfection was detected for the secondary effluent due to its lower TOC amount, enabling the attack of bigger amounts of electrogenerated oxidants on microorganisms. Wastewater killing microorganisms by E-F was also practicable at natural pH (~7), illustrating identical reduction of active microorganisms as a consequence of the synergistic action of oxidants produced such as active chlorine and coagulation with iron hydroxides. A sequential EC/E-F treatment (30 min each) was more efficient for combined decontamination and disinfection of urban wastewater.

Moreover, Delaire et al. [136] focused on Fe-EC, which is considered a low-cost method in which Fe(II) formed from an Fe(0) anode reacts with dissolved O_2 to produce (1) Fe(III) precipitates with an affinity for bacterial cell walls and (2) bactericidal reactive oxidants. Employing the model indicator *E. coli*, they illustrated that physical removal via enmeshment in EC precipitate flocs is the fundamental operation of bacteria inactivation in the presence of HCO_3^-, which significantly hinders deactivation, likely because of a decrease in the lifetime of reactive oxidants. They established that the cohesion of EC precipitates to cell walls, which leads to bacteria encapsulation in flocs, is imposed firstly by interactions between EC precipitates and phosphate functional groups on bacteria surfaces. In only one solute electrolytes, both P (0.4 mM) and Ca/Mg (1–13 mM) blocked the cohesion of EC precipitates to bacterial cell walls, whereas Si (0.4 mM) and ionic strength (2–200 mM) did not affect *E. coli* reduction. Significantly, P (0.4 mM) did not impact *E. coli* decrease in electrolytes carrying Ca/Mg, consistent with bivalent cation bridging between bacterial phosphate groups and inorganic P sorbed to EC precipitates. Finally, EC precipitates cohesion is greatly independent of cell wall composition, consistent with comparable densities of phosphate functional groups on Gram-positive and Gram-negative cells. Such findings may be crucial to predicting the efficiency of Fe-EC to remove bacterial contaminants from waters with diverse chemical compositions.

In addition, Gökkuş and Yildiz [137] applied EC [138] for the treatment of medical waste sterilization plant wastewater and examined phosphate and chemical oxygen demand (COD) removals. They optimized four crucial parameters:

initial pH, current density, initial wastewater concentration, and residence period. At optimum conditions, they found that about 52% of COD reduction has been reached and phosphorus has been eliminated. The contribution percentages of each parameter in descending order are as follows: initial wastewater concentration (42.51%) > pH (32.02%) > current density(14.56 %) > contact time (6.64 %).

Moreover, Boudjema et al. [139] studied the likely treatment of Oued El Harrach river (Algeria) water by Al EC [140]. In batch experiments, COD and turbidity were decreased by ~80% and 95%, respectively, within 30 min. A 99% reduction in fecal coliforms and *E. coli* was obtained and a near-total inactivation of fungi was reached.

In addition, Zaleschiet al. [141] examined the disinfection capacity of EC with Fe and Al electrodes. They tested two different effluents of conventional WWTPs. They proved that EC is capable of decreasing COD, turbidity and nutrients. In the same way, EC does not act on conductivity (the opposite of the classical coagulation–flocculation process) and helps buffer pH in a value ~8. Precipitation, floc enmeshment and adsorption appear to be the fundamental mechanisms in this technique. Concerning the reduction of fecal coliforms, this approach proceeds like a disinfection technique. Energy consumption lower than 0.2 kWh/m^3 is needed to achieve standard disinfection levels. Similar results are obtained by several researchers [114,142–146].

The EC mechanisms of artificial wastewater contaminated by *E. coli* culture (5×10^5 UFC/100 mL) were examined by Ndjomgoue-Yossa et al. [138]. They made a comparison of comportments of two electrodes of the dissolved-type (Fe and Al) and an electrode of the non-dissolved-type (carbon graphite). The Fe electrode was observed to be more performant than Al and carbon graphite electrodes for *E. coli* cells inactivation. Their study also covered the influence of different supporting electrolytes: sodium chloride, sodium sulfate and sodium nitrate. *E. coli* was deactivated by 5 log units for a charge loading of 37.30 F/m^3 for sodium sulfate, 24.87 F/m^3 for sodium nitrate and 12.43 F/m^3 for sodium chloride. Their conclusion was that sodium chloride is the most favorable supporting electrolyte type due to the generation of disinfectants like chlorine dioxide, hypochlorite ions and perchlorate ions. Therefore, three combined effects follow EC implemented to the removal of *E. coli*: the actions of oxidants electrogenerated during the process, the EF [2], and the adsorption by the metallic hydroxides formed in solution.

A biological cell is made of a cytoplasm inside a membrane [139]. The cytoplasm is usually considered an electrical conductor and the membrane, made up of a lipid layer, an insulator. Cell membrane polarization is produced by imposing and EF [2]. The membrane is meant [140] to act as a capacitor; the opposite charges present on the opposite sides of the membrane generate an initial transmembrane potential. A transmembrane potential augmentation may be produced by a charge accumulation detected on the membrane surface. The bacterial cell between two electrodes acts as an insulator; its plasma membrane is polarized [139].

On the other hand, Llanos et al. [147] compared the efficiency of EC in two steps of the urban water cycle: drinking water production and wastewater regeneration. They performed a case study focused on the treatment of actual effluents from different locations in Spain. They found that Al EC is an effective method to eliminate turbidity and TOC from surface water and to deplete turbidity and *E. coli* from urban treated wastewater. They concluded that, even if EC may be used in the treatment of both effluents, the method is more effective in the case of the production of drinking water from surface sources. This comportment is attributed to the nature of the NOMs present in both effluents.

Moreover, Moreno et al. [148] established that EC is a possible technique for the treatment of municipal wastewater in Mexico. They illustrated a noticeable elimination performance for: COD 77-94%, coliforms 80%, and CFU 99.98% within only 30 s of the contact period.

In addition, Ricordel et al. [149] examined the mechanism of *E. coli* reduction during Al EC. Employing the same quantities of Al, EC presented bigger bacteria inactivation by a 2-log factor than for chemical coagulation. They found that decanted EC flocs carried living bacteria proposing that *E. coli* elimination through the EC process may be linked to powerful bacteria cohesion on the surface of alumina particles produced. Chopra and Sharma obtained similar results [150].

Moreover, Boudjemaet al. [151] examined the effect of abiotic factors and their mutual action on the bactericidal effects of EC. They investigated the kinetics of bacterial density *vs.* time and some abiotic parameters like pH, conductivity, turbidity, total suspended solids, and COD, by fixing the intensity of the current to 3 A employing Al electrodes. They as well followed the comportment of bacteria towards the electric current through evaluating the mortality rate (log 10) or bacterial survival (UFC/mL) after treatment. Their findings proved that the removal rate of the bacteria is 6 log 10 with an important correlation ($R_2 = 0.98$) by augmenting the time. A powerful correlation ($R_2 = 0.93$) was obtained with the pH augmentation. A positive correlation has been observed with the removal of bacterial biomass and COD and negative with total suspended solids.

Also, Barrera-Díaz et al. [152] estimated the influence of copper EC and hydrogen peroxide on COD, color, turbidity, and bacterial activity in mixed industry wastewater. The merged system of CuEC and H_2O_2 is efficient at decreasing the organic and bacterial content of industrial wastewater. The CuEC single decreases COD by 56% in 30 min at pH 2.8; however, the joined system decreases COD by 78%, biochemical oxygen demand by 81%, and color by 97% upon the identical parameters. Colloids are flocculated efficiently, as illustrated by the decrease of zeta potential and the 84% decrease in turbidity and 99% decrease in total solids. Moreover, the total coliforms, fecal coliforms, and bacteria are all diminished by 99%.

Finally, Delaire [153] studied bacteria reduction using Fe-EC. She established that Fe-EC might reduce bacteria in synthetic Bengal groundwater without detriment to arsenic remediation. She consistently explored the effect of operating parameters (Fe dosage and dosage rate), groundwater composition (pH, HCO_3^-, Ca, Mg, Si, P, and NOM, and bacteria type, with a center of attention on clarifying the stages of bacteria inactivation. Her findings established that inactivation is mainly related to bacteria encapsulation in Fe(III) flocs and elimination by gravitational settling, while attenuation upon germicidal reactive oxidants stays restricted in the presence of HCO_3^- and at pH > 7. Fe(III) precipitates are observed to bond to the surface of bacterial cells, mainly by mutual actions with bacterial phosphate groups, conducting to bacteria enmeshment in precipitate flocs. The impact of main groundwater ions is explained following this mechanism: Ca and Mg decrease in activation through complexing bacterial phosphate groups; Si and NOM, which do not strongly compete with phosphate groups for sorption to Fe(III) precipitates and do not influence in activation; on the other hand, P reduces inactivation significantly, unless in the existence of bivalent cations, which may bridge between P sorbed to precipitates and bacterial phosphate groups. Eventually, Fe-EC is established to, in the same manner, be efficient towards Gram-positive and Gram-negative bacteria, smooth and rough alike, probably because of the universal existence of phosphate moieties on bacterial cell walls. Generally, her findings prove that Fe-EC may efficiently eliminate all types of bacterial pollution from a range of waters [153–155].

5. Future trends in EC process for disinfection

Based on the coupling of EC with other AOPs, novel processes have recently been developed [156,157]: UV light irradiation [158,159] and Fenton electrochemically assisted [117]. Pertinent information about the novel systems for disinfection related to the combination of EC and other technologies has been provided by some researchers. Cotillas et al. [159], for example, worked on an interesting hybrid technique for reusing of urban treated wastewaters. Another option is the crossbred technique, which concerns the use of UV irradiation to an EC method with Al electrodes (i.e., photo-EC). The findings of Cotillas et al. [159] demonstrate that the concurrent elimination of the pathogen microorganisms and colloids in wastewater is by imposing low current densities. Coagulant species are generated upon the electrodissolution of the Al anode, using the photo-EC technique; this eliminates colloidal particles in wastewater. The coagulant species are mostly a function of the pH and the dissolved Al amount. It was noted by Cotillas et al. [159] that the pH through the photo-EC method persisted fixed (~8).At this pH degree, the generation of insoluble Al hydroxides is privileged, as is a sweep flocculation [122] as principal coagulation procedure. In addition, the existence of free and combined chlorine disinfectants in wastewater was detected by these researchers through this hybrid process. Since urban wastewater usually has significant amounts of chlorides, these chemicals can be oxidized on the anode, which the formation of hypochlorite [5]. Also, the use of UV radiation through this combined technique enables the elimination of microorganisms due to the mutual action of the light on the cell membrane of *E. coli*. Similarly, the use of UV light through the EC promotes the production of free radicals from the oxidizing species generated previously. These chemicals enhance the technique efficiency in matters of *E. coli* decrease and encourage the chemical dissolution of the sacrificial anode; therefore, there is an augmentation in the colloids elimination efficiency.

Similarly, according to Anfruns-Estrada et al. [117], a sequential EC/E-F treatment (30 min each) is more efficient for combined decontamination and disinfection of urban wastewater [160].

6. Conclusions

The main important points drawn from this review may be listed as:

1. A biological cell consists of a cytoplasm enclosed by a membrane [139]. The cytoplasm can be viewed as an electrical conductor and the membrane, consisting of a lipid layer, as an insulator. Imposing an EF [2] produces cell membrane polarization. The membrane is supposed [140] to act such as a capacitor, with opposite charges present on the opposite sides of the membrane, which generates an initial transmembrane potential. A charge accumulation was detected on the membrane surface; this may produce a transmembrane potential augmentation. The bacterial cell between two electrodes acts as an insulator; its plasma membrane is polarized [139].
2. Employing the model indicator *E. coli*, physical removal via enmeshment in EC precipitate flocs is the fundamental operation of bacteria inactivation in the presence of HCO_3^-, which significantly hinders deactivation, likely because of a decrease in the lifetime of reactive oxidants. The cohesion of EC precipitates to cell walls, which leads to bacteria encapsulation in flocs, is imposed firstly by interactions between EC precipitates and phosphate functional groups on bacteria surfaces. EC precipitate cohesion is greatly independent of cell wall composition, consistent with comparable densities of phosphate functional groups on Gram-positive and Gram-negative cells. Such findings may be crucial to predicting the efficiency of Fe-EC to remove bacterial contaminants from waters with diverse chemical compositions.
3. Even though the idea of using electrical current to dissolve coagulants and produce oxidants *in situ* has a long history, EC has not yet received a firm foothold in water/wastewater treatment. Not long ago, much work was done to clarify several efficiency features comprising pH profiles between electrodes, precipitated solid phases, electrode passivation, and additional parameters affecting EC efficiency. Nevertheless, much more effort is needed because a global comprehension of the nature and composition of precipitated phases based on water chemistry and electrolysis conditions continues to remain elusive. Moreover, preparatory cost evaluations affirm that EC is competitive to classical coagulation particularly for smaller installations.
4. AOPs have been largely described as near ambient temperature treatment processes based on highly reactive radicals, especially the hydroxyl radical ($^•OH$) as the main oxidant. In addition, if the electrochemical reactors function at an elevated cell potential and an anodic phenomenon happens in the potential region of water discharge, hydroxyl radicals ($^•OH$) are produced. To have more probabilities to have free radicals generation during EC, ultrasound through EC may be very helpful. Moreover, the EC process at pH less than 3 possesses more probability to form hydroxyl radicals. Recently, Medel et al. [7] worked on the same research axis suggested five years ago.

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