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Electrocoagulation Process in the Context of Disinfection Mechanism

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Abstract

During the last three decades, the electrocoagulation (EC) process has known an exemplary renaissance in the field of water and wastewater treatment. Several researchers focused on applying this electrochemical technology in removing diverse pollutants such as pathogens. During EC method, the coagulant is furnished via solubilizing sacrificial electrodes upon an applied electric field. The easiness of the technology and the side phenomena involving the generation of gas bubbles are the major advantages. This work discusses briefly the main achievements and mechanisms in employing EC in disinfecting water. In the EC process, the microbes may be demobilized thanks to the direct adsorption on the surface of the anode pursued by electron transfer, and physical elimination through floating pathogens with formed hydrogen gas and/or precipitating with the produced flocs. Integrating EC with free radical assisted processes (e.g., electrooxidation), magnetic field and/or ultrasonic field remains an encouraging method to promote its implantation at full scale. Membrane processes should be considered as safe barriers towards disinfection by-products and hydroxyl radicals.

Subject Areas

Environmental Sciences

Keywords

Electrocoagulation (EC), Electrochemical Disinfection, Disinfection Mechanism, Wastewater Treatment, Organic Matter, *Escherichia coli*

1. Introduction

During the last decades, there is no doubt that water and wastewater treatment

industry has known a marked advance [1] [2]. However, water contamination has likewise greatly augmented due to the uncontrolled industrial expansions [3] [4] [5]. As a result, the at hand water resources became contaminated with a large range of contaminants generating various health issues [6] [7]. Some of such contaminants, the pathogenic and non-pathogenic microorganisms are categorized at the most elevated danger than remaining contaminants because of the towering cases of illness and death that they could provoke [8] [9] [10] [11]. For example, it has been mentioned that the pathogens trigger diverse waterborne diseases, like diarrhea and gastrointestinal, which successively lead to around 2,000,000 deaths/year [8] [12]. Thus, several disinfection techniques, like chlorination [13] [14] [15] [16], ozonation, and irradiation with ultraviolet, have been employed to kill pathogenic and non-pathogenic microorganisms from water [17]-[24]. As an illustration, chlorination process has been largely employed in the course of the 1970s as an efficacious and low-cost disinfection technique. During this chemical method, the strong oxidizing capacity of chlorine destructs the fundamental enzymes of microbes, which conducts to killing such biological contaminants [25] [26]. The primary drawback of chlorination process remains the formation of very poisonous disinfection by-products (DBPs). For example, the reaction among the chlorine and natural organic matter (such as humic substances [27]-[32]) forms trihalomethanes, which are famous as carcinogenic chemicals [25] [26]. Membrane processes, such as microfiltration and ultrafiltration techniques, are additionally efficient barriers for eliminating microbes; nevertheless, their implementing is considerably restricted via the fouling issues and the elevated operational cost [1]. Ozonation is different method that has been utilized as a disinfection technology; indeed, it has been noted that the ozone is a strong oxidant that can demobilize the microbes via breaking down their cell membrane [25] [33]. Even if the ozonation method is very efficacious and it does not form trihalomethanes like chlorination, it remains costly as contrasted to various conventional techniques [34]; further, it has been established that it may provoke the production of N-nitrosodimethylamine [33].

Lately, the disinfection engineering has known outstanding progress through merging several technique or via employing novel composite materials. For instance, researchers [35] suggested a fresh disinfection process that employs a tubular coaxial-electrode copper ionization cell to disinfect drinking water. The acquired findings depicted that this technique eliminated 6-log of *Escherichia coli* during 2 min of application at running voltage of 1.5 V. Scientists [36] employed advanced electrochemical cell that was furnished with boron doped diamond electrodes to disinfect seawater. The results of this investigation proved that this advanced electrochemical cell reduces 4.8-Log of natural marine heterotrophic bacteria at energy consumption of 0.264 kWh/m^3. The same researchers [36] implements the nanotechnology [37] to present a disinfection technology that comprise an anodic multiwall carbon nanotube filter to kill viruses and *E. coli* in water. They discovered that such technique diminished the number of viruses and *E. coli*, during 30 s at voltage of 3 V, to below detection limit [1].

Electrocoagulation (EC) process has lately received a big deal of focus as an efficient technology to eliminate microbes from wastewater and water thanks to its simplicity, selectivity, and comparatively low operating cost [38]-[44]. Further, the EC technique does not require chemicals injections to elevate the treatment performance (except for the case where the ionic strength is weak so supporting electrolyte should be added to increase the solution electric conductivity [45]), and it may be with ease automated and combined with additional treatment setups [46] [47] [48]. In addition, EC technology hugely decreases the volume of the formed solid waste (sludge) that needs elevated treatment cost [49] [50]; which successively greatly reduces the working price of the EC technique [51] [52]. These merits of the EC process place it extremely encouraging choice to the classical treatment techniques [53] [54] [55]. On the other hand, absence of reactor design (simple horizontal or vertical arrangement of square or rectangular plate electrodes inside a container) and the care of the EC to the chemical composition of the liquid being handled constitute the major obstacles of the EC technology [1] [51] [56] [57] [58].

2. Electrocoagulation Process in Terms of Disinfection Pathways

The literature presents numerous explications for the routes of killing microorganisms via electrochemical technologies, which could be listed in **Table 1** [19] [59] [60] [61].

In the EC process, in addition to the aforesaid routes, the microbes may be demobilized thanks to the direct adsorption on the surface of the anode pursued by electron transfer, and physical elimination through floating pathogens with formed hydrogen gas and/or precipitating with the produced flocs [34] [59] [60]. **Table 2** presents the detailed EC reactions in the case of Fe [62] and Al electrodes.

More importantly, so powerful oxidizing agents, like HOCl, OCl^-, ClO_2 and Cl_2, are formed throughout the EC technology following the next reactions [59] [67]:

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (16)$$

$$Cl_2 + 2OH^- \rightarrow H_2O + OCl^- + Cl^- \quad (17)$$

$$Cl_2 + 4H_2O \rightarrow 2ClO_2 + 8e^- \quad (18)$$

Table 1. Principal actions proposed explaining the deadliness of the electrochemical disinfection [19].

Electrochemical Disinfection Tools	
Oxidants	*Electric Field*
Oxidative stress and cell loss of life.	1) Irreversible permeabilization of cell membranes. 2) Electrochemical oxidation of vital cellular constituents. 3) Electrosorption of negatively charged *E. coli* cells to the anode surface + direct electron transfer reaction.

Table 2. EC mechanisms using Fe (pH 2, 7 and 12) and Al (pH 7) electrodes [63] [64] [65] [66].

Fe mechanisms		
*Mechanism #*1 (pH 2)	Anode:	
	$2Fe_{(s)} - 4e^- \rightarrow 2Fe^{2+}_{(aq)} \quad (E° = +0.447\ V)$	(1)
	$2H_2O_{(l)} - 4e^- \rightarrow O_{2(g)} + 4H^{2+}_{(aq)} \quad (E° = -1.229\ V)$	(2)
	Solution:	
	$2Fe^{2+}_{(aq)} + 4OH^-_{(aq)} \rightarrow 2Fe(OH)_{2(s)}$	(3)
	Cathode:	
	$8H^+_{(aq)} + 8e^- \rightarrow 4H_{2(g)} \quad (E° = 0.000\ V)$	(4)
	Total:	
	$2Fe_{(s)} + 6H_2O_{(l)} \rightarrow O_{2(g)} + 4H_{2(g)} + 2Fe(OH)_{2(s)}$	(5)
*Mechanism #*2 (pH 7)	Anode:	
	$2Fe_{(s)} - 4e^- \rightarrow 2Fe^{2+}_{(aq)} \quad (E° = +0.447\ V)$	(1)
	$Fe^{2+}_{(aq)} - e^- \rightarrow Fe^{3+}_{(aq)} \quad (E° = -0.771\ V)$	(6)
	$Fe_{(s)} - 3e^- \rightarrow Fe^{3+}_{(aq)} \quad (E° = +0.037\ V)$	(7)
	Solution:	
	$Fe^{2+}_{(aq)} + 2OH^-_{(aq)} \rightarrow Fe(OH)_{2(s)}$	(3)
	$2Fe^{3+}_{(aq)} + 6OH^-_{(aq)} \rightarrow 2Fe(OH)_{3(s)}$	(8)
	Cathode:	
	$8H_2O_{(l)} + 8e^- \rightarrow 4H_{2(g)} + 8OH^-_{(aq)} \quad (E° = -0.828\ V)$	(9)
	Total:	
	$3Fe_{(s)} + 8H_2O_{(l)} \rightarrow Fe(OH)_{2(s)} + 2Fe(OH)_{3(s)} + 4H_{2(g)}$	(10)
*Mechanism #*3 (*pH* 12)	Anode:	
	$2Fe_{(s)} - 6e^- \rightarrow 2Fe^{3+}_{(aq)} \quad (E° = +0.037\ V)$	(7)
	Solution:	
	$2Fe^{3+}_{(aq)} + 6OH^-_{(aq)} \rightarrow 2Fe(OH)_{3(s)}$	(8)
	Cathode:	
	$6H_2O_{(l)} + 6e^- \rightarrow 3H_{2(g)} + 6OH^-_{(aq)} \quad (E° = -0.828\ V)$	(9)
	Total:	
	$2Fe_{(s)} + 6H_2O_{(l)} \rightarrow 2Fe(OH)_{3(s)} + 3H_{2(g)}$	(11)
Al mechanism		
Mechanism (*pH* 7)	Anode:	
	$Al_{(s)} - 3e^- \rightarrow Ale^{3+}_{(aq)} \quad (E° = +1.66\ V)$	(12)
	$2H_2O_{(l)} - 4e^- \rightarrow O_{2(g)} + 4H^+_{(aq)} \quad (E° = -1.229\ V)$	(2)
	Solution:	
	$Al^{3+}_{(aq)} + 3OH^-_{(aq)} \rightarrow Al(OH)_{3(s)}$	(12)
	$Al(OH)^-_{4(aq)} \rightarrow OH^-_{(aq)} + Al(OH)_{3(s)}$	(13)
	Cathode:	
	$4H_2O_{(l)} + 4e^- \rightarrow 2H_{2(g)} + 4OH^-_{(aq)} \quad (E° = -0.828\ V)$	(9)
	$Al_{(s)} + 4OH^-_{(aq)} - 3e^- \rightarrow Al(OH)^-_{4(aq)}$	(14)
	Total:	
	$2Al_{(s)} + 8H_2O_{(l)} \rightarrow 5H_{2(g)} + 2Al(OH)_{3(s)} + O_{2(g)}$	(15)

Such chemicals may harm the membrane of the cell that leads to killing microbes.

3. Electrocoagulation Employing Baffle-Plates Electrodes for Eliminating *Escherichia coli*

Hashim *et al.* [1] suggested a novel EC device, which employs the notions of baffle-plates, for eliminating *E. coli* from wastewater (Figure 1). Such aluminum-based EC setup employs perforated baffle-plates electrodes to mix water, which decreases the necessity of mechanical or magnetic mixers that need additional power to run (Figure 2). They handled wastewater samples carrying *E. coli*, taking into account the impacts of treatment time (TT), inter-electrode distance (IED), and current density (CD). Their findings proved that the device reduces as high as 96% of the *E. coli* during 20 min of electrolysis at IED of 0.5 cm, and CD of 1.5 mA/cm^2. Further, the working price of the suggested setup is 0.11 US \$/m^3 (for *E. coli* elimination), which is less than working price of conventional devices. They noted that the influence of the investigated factors on *E. coli* elimination pursued the order: TT > CD > IED.

4. Ultrasonication of Electrocoagulation Reactor for Killing *Escherichia coli*

Once again Hashim *et al.* [68] proposed a fresh hybrid ultrasonic-EC device to demobilize *E. coli* in water. The novel hybrid setup is composed of an ultrasonic bath fitted with four perforated aluminum electrodes. Such perforated electrodes are conceived to work as baffle-plates to improve the water-mixing phenomena (Figure 3). As mentioned in the previous Section, such metallic plates avoid the necessity of external mixing devices. At first, they regulated the capacity of the EC to demobilize *E. coli* for electrolyzing time, electrodes spacing and current density. The ultrasonic field was subsequently implemented through varying

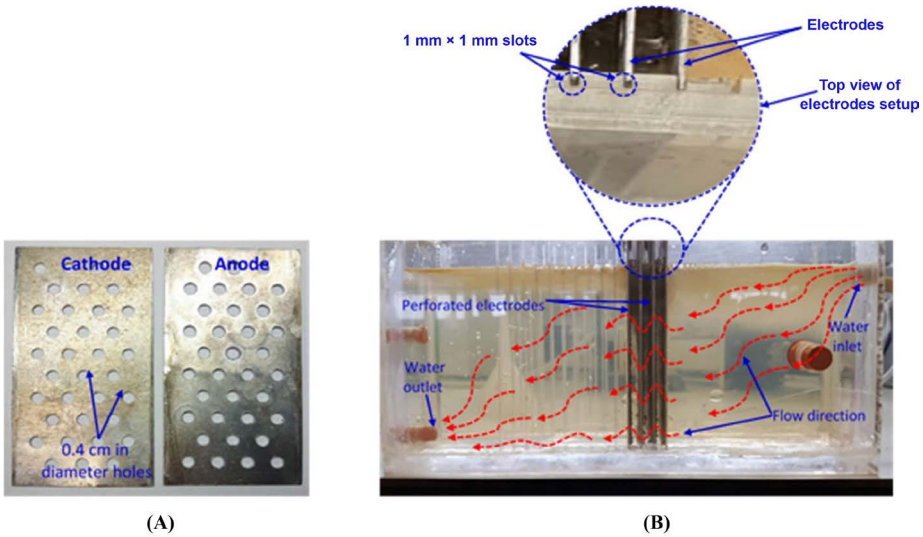

Figure 1. (A) Electrodes, (B) baffle-plates aluminum-based EC reactor [1].

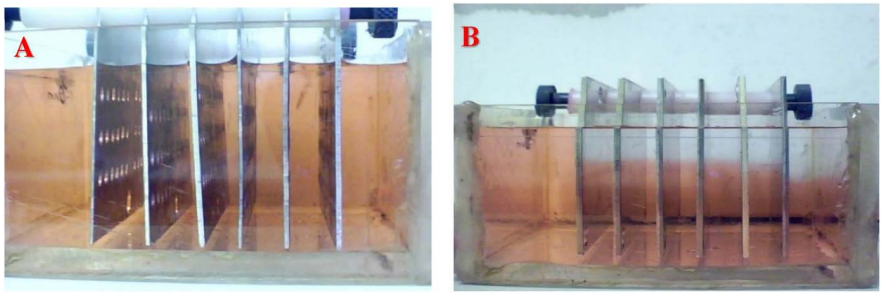

Figure 2. Mixing efficiency of (A) baffle-plates aluminum-based EC reactor, (B) A traditional EC reactor [1].

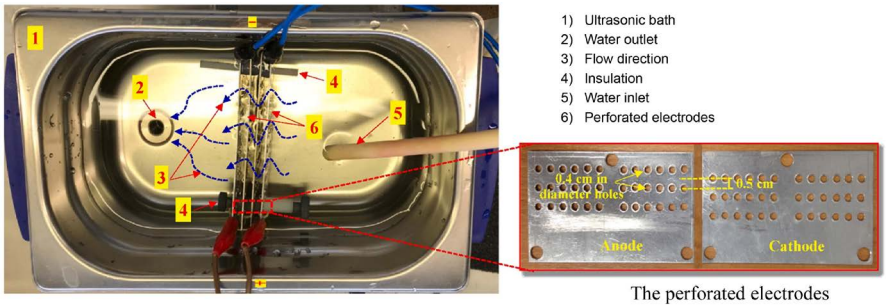

Figure 3. The ultrasonic-EC reactor [68].

time periods, over the period of the electrolyzing method. They proved that the new ultrasonic-EC device killed 100% of the *E. coli* in 11 min of electrolysis at electrodes spacing of 5 mm, current density of 1.5 mA/cm^2, and an operation cost of 0.212 US \$/m^3.

5. EC Next Tendencies

As mentioned previously, EC stays a viable solution for classical coagulation, through which the coagulant is furnished via solubilizing sacrificial electrodes upon an applied electric field [34] [69]. The easiness of the technology and the side phenomena involving the generation of gas bubbles are the major advantages. Even if the laboratory design of an EC cell is extremely easy, its scale-up is not as simple, especially for large water treatment plants. It is not frequently ready to employ tank cells with sheets of Fe and Al, and there is a necessity to employ cheap materials as sacrificial electrodes. Employing low-quality Fe or Al may enable bipolar electrode configurations to be used. Integrating EC with free radical assisted processes (e.g., electrooxidation), magnetic field [66] [70] [71] [72] [73] [74] and/or ultrasonic field remains an encouraging method to promote its implantation at full scale [64] [69].

During EC process, there are two induced phenomena: electrophoresis and electroflotation [75]; separately, they are well known in electrochemistry's applications and well developed technically and mathematically [76]. How important are these inherent phenomena in EC process efficiency, particularly in removing pathogens deserves more focus [77].

The superior performance of ferrate (VI) has been demonstrated through several studies [78]. The practical aspect of many of them was to demonstrate the feasibility of the online generation and application of ferrate (VI) for sewage treatment [79] [80] [81], which could lead to the implementation of ferrate (VI) technology in water and wastewater treatment [82]-[93] practice. Electrochemical generation of ferrate (VI) is similar to EC process. Consequently, merging ferrate (VI) produced electrochemically with EC [94] [95] [96] [97] constitutes an interesting field of research [98] [99].

Membrane processes should be considered as safe barriers towards DBPs and hydroxyl radicals' (probably generated during EC process [64]) removal [100]-[105].

6. Conclusions

From this work, the following conclusions can be drawn:

1) A recent study proved that baffle-plates aluminum-based EC reactor has the potential to kill 96% of *E. coli* from synthetic wastewater, which is identical to the mentioned performances in the literature [1]. Further, the baffle-plates aluminum-based EC reactor consumes less energy than conventional units perform since it does not necessitate external water mixing devices. *E. coli* reduction is more considerable at high current densities and long residence time. Perversely, eliminating *E. coli* is reversely proportional to the distance separating the electrodes. The contact period is the most important parameter in killing *E. coli*; however, the gap among the anode and the cathode has the lowest effect.

2) A fresh hybrid ultrasonic-EC device was presented to kill *E. coli* existing in water [68]. The setup may be a helpful and cost-efficient choice to classical methods for disinfecting water. The survivability of *E. coli* considerably diminishes with an elevation of the electrolyzing period, ultrasonication time or applied current density. As a perspective, studying the pathways of *E. coli* demobilization employing the combined EC with ultrasonication merits more attention.

3) In the EC process, the microbes may be demobilized thanks to the direct adsorption on the surface of the anode pursued by electron transfer, and physical elimination through floating pathogens with formed hydrogen gas and/or precipitating with the produced flocs. Integrating EC with free radical assisted processes (e.g., electrooxidation), magnetic field and/or ultrasonic field remains an encouraging method to promote its implantation at full scale. Membrane processes should be considered as safe barriers towards disinfection by-products and hydroxyl radicals.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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