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Electrocoagulation-Based Removal of *Escherichia coli* from Wastewater: Optimization and Performance Evaluation

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ABSTRACT

Pathogenic microorganisms, such as *Escherichia coli* (*E. coli*), can contaminate water and pose a serious public health risk as indicators of fecal contamination. As these threats grow, effective water treatment solutions are essential. Reusing treated water is a key sustainability strategy, with conventional methods like chlorination, membrane separation, and UV disinfection commonly used. However, these methods have limitations and environmental risks. Electrocoagulation (EC) has gained attention for its efficiency in pathogen removal, cost-effectiveness, and environmental benefits. This study investigated the removal of *E. coli* from industrial wastewater using electrocoagulation with aluminum electrodes, focusing on the effects of initial pH and electrode number. The initial bacterial concentration was 1×10^8 CFU/mL. Results showed that pH significantly affects removal efficiency. The highest removal rates were at pH 5.5, where bacteria were completely removed, and at pH 8.5, where the final concentration was 1.4×10^3 CFU/mL, and achieving 99.9% removal. At neutral pH 7, efficiency dropped to 95%, with a final concentration of 5.1×10^6 CFU/mL. Experiments were conducted under constant conditions (30V, 4 cm electrode spacing), and an increase in the number of electrodes was found to enhance removal efficiency. These findings highlight electrocoagulation's superior disinfection capability over biological treatments and its potential to reduce chlorine usage, making it a promising and eco-friendly water treatment alternative.

1. INTRODUCTION

Without a doubt, the water and wastewater treatment industry has advanced significantly during the past few decades [1, 2]. However, unchecked industrial growth has also significantly increased water contamination [3-5]. Consequently, a wide variety of toxins contaminate the available water supplies, leading to several health problems [6-8]. Because of the elevated risk of disease and death they can cause, some of these contaminants—both pathogenic and non-pathogenic microorganisms—are considered more hazardous than others [9-12]. For example, it has been noted that bacteria cause a variety of waterborne illnesses, such as gastrointestinal and diarrheal disorders, which together result in over 2,000,000 fatalities annually [9, 13, 14]. Waterborne illnesses caused by bacterial contamination are a major concern for the global health community [15]. *Escherichia coli* is considered an indicator of fecal contamination and is among the bacteria responsible for intestinal infections [16-18]. Scientists have found that more than 30 ponds in a rural area of Bangladesh have been contaminated with *E. coli*. Particularly in poor and emerging countries, this problem is made worse by the absence or insufficiency of contemporary treatment approaches [19]. The primary objective of most conventional treatment plants is to remove contaminants. However, they are not highly effective in disinfecting water and eliminating pathogenic microorganisms [20]. Chlorine is the most commonly utilized method worldwide, working in roughly 90% of water treatment plants because of its simplicity, small price, and elevated effectiveness. Chlorine is a significant biocidal agent, but it's not appropriately utilized, and sometimes, it is utilized excessively. In addition to water, chlorine, in its various shapes, responds with organic materials that occur naturally, producing by-products like trihalomethanes (THMs). These substances, according to reports, cause different diseases, including cancer [21, 22]. Consequently, several studies have been carried out to reduce the amount of biological contaminants through the use of low-cost and efficient treatment methods like disinfection and coagulation [19]. The electrochemical technique has gained considerable attention in wastewater remediation [23, 24]. One of the emerging technologies that demonstrated its effectiveness in opposition to a wide range of microorganisms is electrochemical disinfection (ED) [25]. It's acquired a growing focus as a substitute to traditional disinfection techniques because it is environmentally friendly and is known to deactivate a broad diversity of microorganisms (bacteria, viruses, and algae). Recent research has shown that electrocoagulation, an electrochemical disinfection technique, provides a compelling substitute for traditional methods of treating germs while using comparatively little energy [15, 26]. Additionally, the EC method significantly reduces the volume of generated solid waste (sludge), which requires high treatment costs [27-30]. This, in turn, lowers the overall operational cost of the EC method. This study aims to treat wastewater with *E. coli* by using an electrocoagulation technique at different pH values and various periods.

2. METHODOLOGY

2.1 Mechanism of disinfection

The literature presents various interpretations of the mechanisms underlying the deactivation of microorganisms, which can be categorized as follows [29, 30].

1. Cell lysis as a result of cell wall damage;
2. Cytoplasmic membrane permeabilization, which permits the departure of vital nutrients;
3. Modifying the characteristics of protoplasm, which may be seriously harmed by exposure to light, heat, or pH shock;
4. Oxidizing chemicals can change the function of enzymes by destroying their chemical structure, which can have fatal consequences.

2.2 Electrocoagulation disinfection mechanism

The EC reactor configuration differs in the number of electrodes and arrangement of electrodes monopolar or bipolar. Figure 1 illustrates the electrochemical method's reaction mechanism.

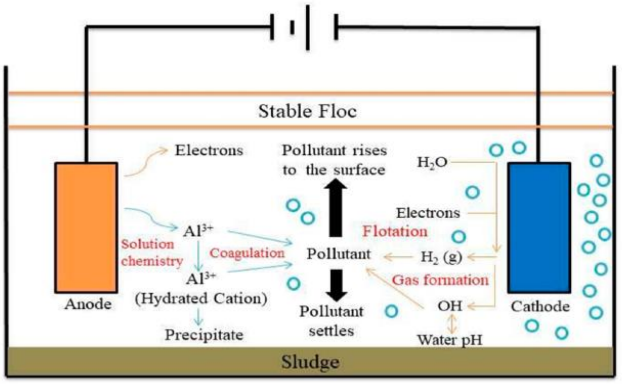

Figure 1. Electrocoagulation disinfection mechanism [31]

Anodic material oxidizes and cathodic material reduces in response to an applied electric current [32]. In addition to the previously described processes, the EC method may deactivate the microorganisms by straight adsorption to the anode surface, then electron movement and physical elimination through flotation of the microorganisms with the hydrogen gas produced and/or precipitation with the flocs generated [28, 30]. The following reactions will occur if aluminum electrodes are used [33]:

$$Al \rightarrow Al_3^{+} + 3e^{-} \quad \text{(Anode)} \tag{1}$$

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-} \quad \text{(Cathode)} \tag{2}$$

When using aluminum anodes, the redox reactions that take place include [34]:

$$2H_2O + 2e^{-} \rightarrow H_2(g) + 2HO_{(aq)}^{-} \quad \text{(Cathode)} \tag{3}$$

$$2H_2O \rightarrow O_{2(g)} + 4H_{(aq)} + 4e^{-} \quad \text{(Anode)} \tag{4}$$

The steps in an electrochemical process are as follows: (1) Electrolysis at electrodes, which produces OH ions at the cathode and aluminum ions at the anode; (2) Aluminum ion oxidation, which results in the precipitation of $Al(OH)_3$; and (3) Colloidal or soluble contaminants adsorb onto coagulants, which are then eliminated by physical means.

In the EC method, in addition to the mechanisms mentioned, microorganisms can be disrupted by direct adsorption on the surface of the anode followed by the transfer of electrons. They can also be physically removed by floating with hydrogen gas generated during the process or precipitating with the sediment formed [1]. During electrocoagulation, an electric field is generated around various pollutants and microorganisms present in the water. Several researchers have explained that this electric field affects the permeability and stability of the cell membrane of bacteria, which can lead to its rupture and the destruction of bacterial cells. In addition, electrochemical reactions play an important role in the elimination of bacteria, as oxidation reactions at the anode and reduction at the cathode cause the formation of hydrogen peroxide, a compound effective in killing bacteria by causing damage to their tissues, leading to their death [20].

2.3 Benefits of the EC approach

The process of the electrocoagulation technique obtained broad attention because of many advantages, which can be summarized as follows [35, 36].

1. Because the EC method uses DC power, which can be generated by the sun, wind, or depleted batteries, it is portable and can be applied in emergencies.
2. The EC is simple to use and doesn't require skilled personnel.
3. Chemicals are not needed in the therapy because the EC creates coagulants using metallic electrodes. Therefore, the EC has no adverse environmental effects.

These benefits account for the EC's widespread use today, particularly in developing nations. The appearance of the inert strata on the aluminum electrodes and the absence of EC unit designs are two minor disadvantages of the EC approach [37].

3. APPLICATION OF PROCESS

The novel idea of electrochemical disinfection (ED) involves passing a low-voltage current between the electrodes [34]. In addition to aiding in the movement of electrons, electrodes can increase and alter the chemical reactions that are occurring to contribute to the electrochemical process. Therefore, the rate at which the oxidants required to inactivate the bacteria are generated is directly influenced by the electrode material. The usage of titanium-based electrodes covered with lead dioxide, mixed metal oxide, platinum, iridium oxide, ruthenium oxide, zirconium dioxide, or titanium dioxide has been the subject of extensive research during the past 20 years [38].

In general, many studies have addressed the elimination of *Escherichia coli* from water and wastewater, including:

Castro-Ríos et al. [39] studied the elimination of *E. coli* from water using aluminum electrodes. The results showed that electrocoagulation was able to remove 1 log after a treatment period of 40 minutes and 1.9 logs after a treatment period of 90 minutes using a pH of 4. Boudjema et al. [40] used aluminum electrodes to eliminate *E. coli* from river water and achieved a 99% reduction.

Riyanto and Agustiningsih [41] conducted a study on the purification of drinking water from *E. coli*. This study was conducted using carbon electrodes. The highest elimination of *E. coli* was obtained after 90 minutes at a voltage of 10 volts.

Hashim et al. [1] studied the elimination of *Escherichia coli* from wastewater by utilizing a reactor based on electrodes with baffle plates made of aluminum and achieved the removal of up to 96% of *Escherichia coli* within 20 minutes at pH 7.

The same researcher, Hashim et al. [42] introduced ultrasound waves with the electrocoagulation reactor (U-E) to remove *Escherichia coli*, also using perforated aluminum electrodes to act as a barrier and using 4 electrodes and achieved 100% removal after 11 minutes of treatment time.

Al-Imara et al. [19] studied the removal of *E. coli* from sewage obtained from the sewage treatment plant in Karbala. Steel plates were used as electrodes. The results indicated that following 40 minutes of therapy time and a current density of 2 milliamps, *E. coli* was killed. Moreover, the results showed that pH 6 is suitable for removing bio-contaminants using electrocoagulation. AL-Jaryan et al. [43] studied the elimination of *E. coli* from municipal wastewater utilizing electrocoagulation based on aluminum electrodes. The results obtained showed that the best inactivation of bacteria was 85.6% at a current density of 2 mA/cm^2 and pH 7.

Ghernaout et al. [44] studied the elimination of *E. coli* from industrial wastewater utilizing regular steel, stainless steel, and aluminum electrodes. They noticed that aluminum electrodes were better at killing *E. coli* cells. The effect of pH (acidic, neutral, and alkaline) and reaction time were studied. The results showed that after 20 minutes of reaction time, the removal rates were 99% at neutral pH and 100% at alkaline pH. After 35 minutes of reaction time, the removal rate approached 100% for acidic and alkaline pH and 98% for neutral pH.

4. MATERIALS AND METHODS

4.1 Synthetic wastewater

Synthetic wastewater was obtained by using the standard *Escherichia coli* ATCC 25922. These bacteria were grown and activated with nutrient broth liquid broth medium at 37°C, and the bacteria were active for 24 hours. When bacteria are added to the system, they are diluted by a saline solution of 9 g of table salt NaCl; this solution is sufficient to keep the cells alive but not reproducible. These standards were gained from the laboratories of the Environmental Research Center-University of Technology-Baghdad-Iraq.

4.2 Electrocoagulation reactor

The electrocoagulation reaction apparatus used in this study was designed to treat a diversity of pollutants. The EC vessel is made of transparent acrylic with dimensions of 20 cm in width, 25 cm in length, and 15 cm in depth and was used to treat 5 liters of wastewater. Aluminum electrodes were used as plates. Each electrode was 15 cm long and 10 cm wide, with a surface area of 150 cm², and was placed vertically and fully immersed in the reactor. The electrodes were connected to a DC power supply (EVENTEK), capable of providing a current of 0–5 Amperes and a voltage of 0–30 Volts. Figure 2 shows the system used in the treatment process.

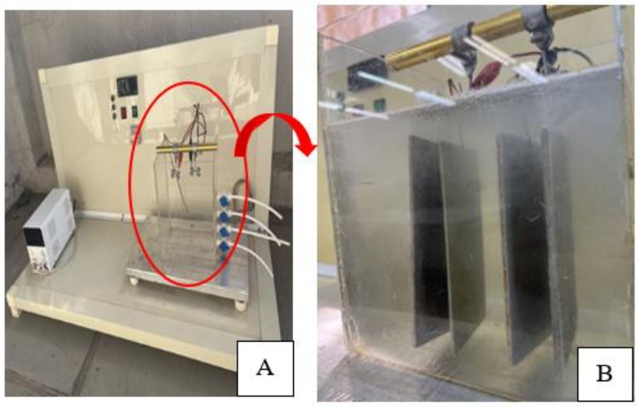

Figure 2. Electrocoagulation reactor (A) reactor with a power source (B) treatment cell with electrodes

4.3 Experimental trials

Test wastewater was prepared by diluting bacteria obtained from the laboratory in distilled water. The testing comprised three categories of experiments: preserving the water's natural pH 7 and, after that, adjusting it to 5.5 and 8.5. 0.1N of HCl and NaOH were added to adjust the pH. The voltage was fixed at 30 V, and the distance between the cathode and the anode was fixed at 4 cm during use in all experiments. Samples were collected at a period of 60 minutes, 120 minutes, and up to 180 minutes of treatment. The effect of the number of electrodes on the elimination of *E. coli* was also studied using 4 and 2 electrodes. The oxides and passivation layers on the electrode are rinsed with HNO_3 diluted in distilled water and then dried. Samples were taken to determine the concentration of *E. coli* and sent to the laboratory. The equation was used to compute the percentage elimination for *E. coli* [45]:

$$R\ \% = \left(\frac{E.coli\ a - E.coli\ b}{E.coli\ a}\right) \times 100$$

where,

R = *E. coli* percent removal,

E. coli a = Initial *E. coli* concentration,

E. coli b = Final *E. coli* concentration.

5. RESULTS AND DISCUSSION

Table 1 shows bacterial test results with various pH and time values, indicating that bacterial count before treatment was 1×10^8 (CFU/mL), voltage 30V, and inter-electrode distance 4cm.

5.1 Treatment duration's impact

With longer treatment times, the growing concentration of metallic ions and associated hydroxide ions enables better contaminant coagulation [46]. As a result, the pollutant removal effectiveness rises in tandem with retention duration, until this effectiveness becomes constant [47]. These experiments were carried out by fixing the operating conditions at 30 volts, a distance between the electrodes of 4 cm, and the number of electrodes of 4 electrodes. The effective area of each electrode was 150 cm^2.

A high percentage of *E. coli* clearance occurs during the first 60 minutes of the treatment period (Figure 3(a, b, c)), reaching 99.9 at a pH of 5.5. Figure 3(b, c) shows that the removal keeps increasing at pH 7 and 8.5 for 120 minutes, reaching 79% and 99.9%, respectively. After 180 minutes, the elimination curve rises to 95% and 100% for each pH of 7 and 5.5, respectively, as seen in Figure 3(a, b). As we can see in Figure 3(c), the removal rate stayed constant at 120 minutes to attain 99.9% even when the reaction period was extended from 120 to 180 minutes for pH 8.5. This is consistent with Boinpally et al. [48], who concluded that the efficiency of removing pollutants remains constant once the appropriate electrolysis time is reached and does not increase with longer electrolysis times. Figures 4 to 6 show the form of coliform bacteria during treatment at different pH values and over varying periods.

Table 1. Experimental design with *E. coli* percentage of elimination

Exp. No.	Number of Electrodes	pH	Time (min)	Final Con. (CFU/mL)	*E. coli* Removal Percentage (%)
1	4	5.5	60	2.3×10^3	99.9
2	4	5.5	120	1.1×10^2	99.9
3	4	5.5	180	No growth	100
4	4	7	60	33×10^6	67
5	4	7	120	21×10^6	79
6	4	7	180	5.1×10^6	95
7	4	8.5	60	1.5×10^5	99.8
8	4	8.5	120	1.2×10^4	99.9
9	4	8.5	180	1.4×10^3	99.9
10	2	5.5	60	41×10^6	59
11	2	5.5	120	28×10^6	72
12	2	5.5	180	64×10^5	94

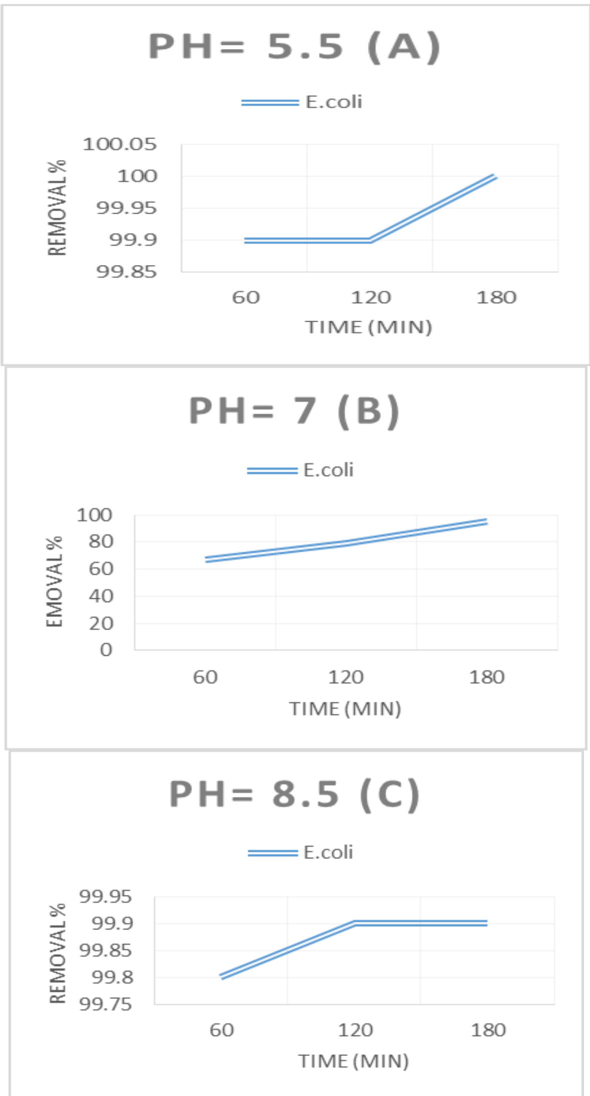

Figure 3. The impact of time on *E. coli* removal at pH (a) 5.5, (b) 7, and (c) 8.5 at voltage=30, inter-electrode distance=4cm, number of electrodes=4

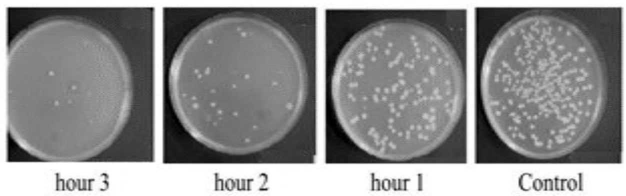

Figure 4. Colony counting after different treating times (60, 120, 180) min at pH=7

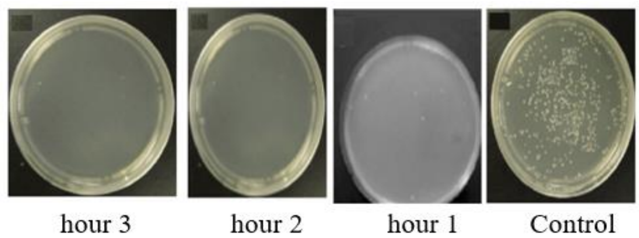

Figure 5. Colony counting after different treating times (60, 120, 180) min at pH=8.5

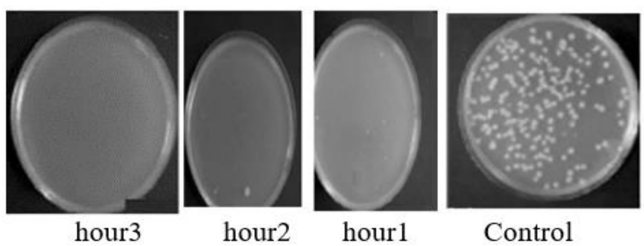

Figure 6. Colony counting after different treating times (60, 120, 180) min at pH =5.5

5.2 pH impact

The starting pH is one of the crucial factors that controls the effectiveness of EC as it influences the rate at which metal hydroxides form [48]. Furthermore, the elimination of bacteria from an aqueous solution is greatly influenced by pH [49]. There have been insufficient studies on how pH affects the elimination of microorganisms during electrocoagulation [25].

Experiments were carried out at pH values of 5.5, 7, and 8.5 for each pH value at a voltage of 30V, a distance between the poles of 4 cm, several poles of 4, and the effective area of each pole is 150 cm², to elucidate the impact of pH on the removal of *Escherichia coli* by EC utilizing aluminum electrodes. It can be observed from Figure 7 that the highest removal rate of *E. coli* was achieved at 100% at pH 5.5 after 180 minutes. The sludge generated after the complete elimination of bacteria was collected, dried at 50℃, and weighed, resulting in a total mass of 0.2 g.

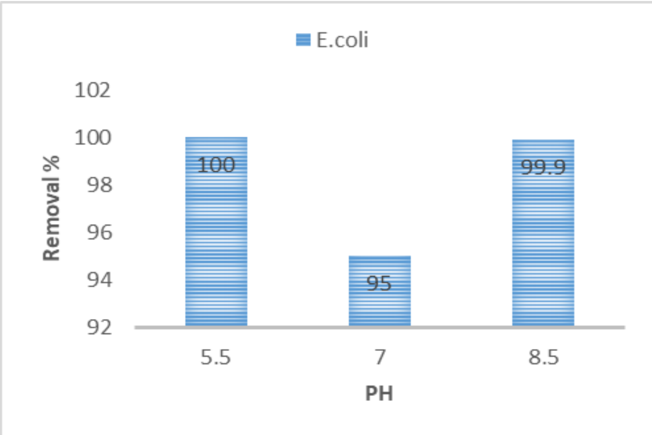

Figure 7. Effect pH on *E. coli* removal at voltage =30, time=180 min, inter-electrode distance=4cm, number of electrodes=4

The highest removal rate was also achieved at pH 8.5, which was 99.9% after 120 minutes. This study is consistent with Ndjomgoue-Yossa et al. [15], which indicated that using aluminum electrodes with a slightly acidic pH of 5.5 can achieve more than 5 log removal of *Escherichia coli*, making it one optimum pH level for this process. The study also indicated that alkaline conditions (pH 8.5, 10) produce similarly high removal rates. However, highly acidic and neutral conditions reduce effectiveness due to increased bacterial resistance.

Due to a combination of many mechanisms, the elimination effectiveness of *Escherichia coli* in solution is better at pH 5.5. This is because the majority of the complexes of hydroxides that cause the coagulation and precipitation of contaminants in solution are generated in the pH vary of 5 to 9. For electrocoagulation, it's the ideal pH range [15]. Due to the interactions between the EC precipitates and the functional groups of phosphate on the surface of the bacteria, the adherence of those precipitates to the cell walls causes the bacteria to be encapsulated in flocs [50].

At pH 8.5, the removal of *Escherichia coli* in solution rises since the rate at which the metal hydroxides that cause the coagulation and adsorption of the contaminants in the solution is elevated [15].

For example, in Al-Al electrodes, the formation of $Al(OH)_3(s)$ leads to an increase in the number of monomeric anionic species, specifically $Al(OH)_4^-$ [51]. Furthermore, the following equation suggests that OH^- ions, generated simultaneously with hydrogen gas (H_2) at high pH levels, could chemically attack the cathode:

$$2(Al) + 6(H_2O) + 2(OH^-) \rightarrow 2(Al(OH)_4) + 3(H_2) \quad (5)$$

These Al complexes, ($Al(OH)_4^-$), polymerize to form micro suspensions, and by the collection of unstable colloids, they become small flocs and after which into bigger flocs. These flocs are thus formed at the origin of the coagulation and precipitation of pollutants in the solution [52].

5.3 Number of electrodes impact

Since the bacteria were eliminated at 4 electrodes after the reaction period ended at a voltage of 30 volts, a distance between the electrodes of 4 cm, and a reaction time of 180 minutes. Figure 8 shows that the removal rate rose dramatically when the number of electrodes was increased from 2 to 4, where the removal rate increased from 59% to 99.9%, from 72% to 99.9%, and from 94% to 100% at 60, 30, and 180 minutes, respectively. This is consistent with Gusa et al. [53], who concluded from their study that the greater the number of electrodes utilized in the electrocoagulation process, the lower the value of pollutants.

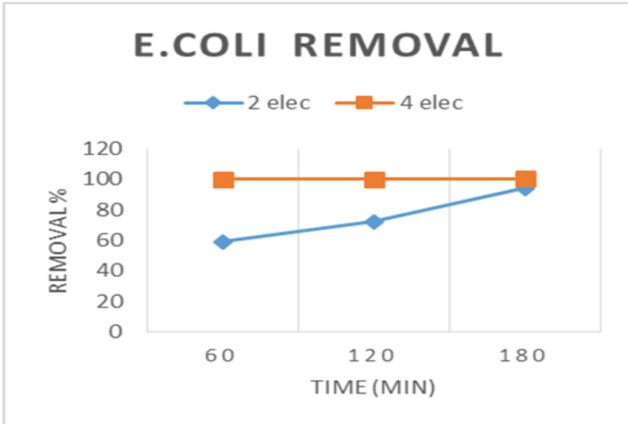

Figure 8. Effect of number of the electrodes on *E. coli* removal at pH=5.5, voltage =30, inter-electrode distance=4cm

The amount of electrical energy consumed at 2 and 4 electrodes was measured as 0.0126 kWh/m³ and 0.03807 kWh/m³, respectively. The amount of electrical energy consumed can be calculated using the following equation [32].

$$E = U \times I \times tEc$$

where, E represents the electrical energy consumed in kWh/L, U represents the cell voltage in volt (V), I represents the current in ampere (A), and tEC is the electrolysis time (min).

6. CONCLUSION

The suggested experimental design indicated that time, pH, and number of electrodes significantly affect the removal rate after 180 minutes of treatment. 100% elimination was accomplished at pH values of 5.5, while a similar value of 99.9% was accomplished at pH 8.5 and 95% removal at pH 7. The best result was obtained when using 4 electrodes in the electrocoagulation process. The results indicate that manipulating the pH, increasing the treatment time, and increasing the number of electrodes used lead to an increase in the removal of *Escherichia coli*, it was shown that electrocoagulation disinfection eliminates a big percentage of pathogenic microorganisms like *E. coli*. This study provides experimental parameters for optimizing EC treatment of *E. coli* in wastewater, providing a reference for future industrial applications.

REFERENCES

[1] Hashim, K.S., Kot, P., Zubaidi, S.L., Alwash, R., Al Khaddar, R., Shaw, A., Al-Jumeily, D., Aljefery, M.H. (2020). Energy efficient electrocoagulation using baffle-plates electrodes for efficient *Escherichia coli* removal from Wastewater. Journal of Water Process Engineering, 33: 101079. https://doi.org/10.1016/j.jwpe.2019.101079

[2] Ghernaout, D., Ghernaout, B., Naceur, M.W. (2011). Embodying the chemical water treatment in the green chemistry—A review. Desalination, 271(1-3): 1-10. https://doi.org/10.1016/j.desal.2011.01.032

[3] Okoh, A.I., Odjadjare, E.E., Igbinosa, E.O., Osode, A.N. (2007). Wastewater treatment plants as a source of microbial pathogens in receiving watersheds. African Journal of Biotechnology, 6(25): 2932-2944. https://doi.org/10.5897/AJB2007.000-2462

[4] Al-Saati, N.H., Hussein, T.K., Abbas, M.H., Hashim, K., Al-Saati, Z.N., Kot, P., Sadique, M., Aljefery, M.H., Carnacina, I. (2019). Statistical modelling of turbidity removal applied to non-toxic natural coagulants in water treatment: A case study. Desalination and Water Treatment, 150: 406-412. https://doi.org/10.5004/dwt.2019.23871

[5] Lombardi, G.V., Stefani, G., Paci, A., Becagli, C., Miliacca, M., Gastaldi, M., Giannetti, B.F., Almeida, C. M.V.B. (2019). The sustainability of the Italian water sector: An empirical analysis by DEA. Journal of Cleaner Production, 227: 1035-1043. https://doi.org/10.1016/j.jclepro.2019.04.283

[6] Dhadge, V.L., Medhi, C.R., Changmai, M., Purkait, M.K. (2018). House hold unit for the treatment of fluoride, iron, arsenic and microorganism contaminated drinking water. Chemosphere, 199: 728-736. https://doi.org/10.1016/j.chemosphere.2018.02.087

[7] Al kindi, G.Y., Al-Haidri, H.A., Hassan, S.A., Al-Hiyaly, S.A. (2022). Environment impact assessment for Al-Rustumiya wastewater treatment plant. Innovative Infrastructure Solutions, 7(2): 162. https://doi.org/10.1007/s41062-022-00767-2

[8] Hashim, K.S., Al-Saati, N.H., Hussein, A.H., Al-Saati, Z.N. (2018). An investigation into the level of heavy metals leaching from canal-dreged sediment: A case study metals leaching from dreged sediment. IOP Conference Series: Materials Science and Engineering, 454: 012022. https://doi.org/10.1088/1757-899X/454/1/012022

[9] Ramírez-Castillo, F.Y., Loera-Muro, A., Jacques, M., Garneau, P., Avelar-González, F.J., Harel, J., Guerrero-Barrera, A.L. (2015). Waterborne pathogens: Detection methods and challenges. Pathogens, 4(2): 307-334. https://doi.org/10.3390/pathogens4020307

[10] Alattabi, A.W., Harris, C.B., Alkhaddar, R.M., Hashim, K.S., Ortoneda-Pedrola, M., Phipps, D. (2017). Improving sludge settleability by introducing an innovative, two-stage settling sequencing batch reactor. Journal of Water Process Engineering, 20: 207-216. https://doi.org/10.1016/j.jwpe.2017.11.004

[11] Baran, W., Adamek, E., Jajko, M., Sobczak, A. (2018). Removal of veterinary antibiotics from wastewater by electrocoagulation. Chemosphere, 194: 381-389. https://doi.org/10.1016/j.chemosphere.2017.11.165

[12] Ghernaout, D. (2017). Environmental principles in the Holy Koran and the Sayings of the Prophet Muhammad. American Journal of Environmental Protection, 6(3): 75-79. https://doi.org/10.11648/j.ajep.20170603.13

[13] World Health Organization. Diarrhoeal disease. http://www.who.int/water_sanitation_health/diseases-risks/diseases/diarrhoea/en/.

[14] Jabri, R.R. (2008). Role of conjugative plasmids in antibiotic resistance. Engineering and Technology Journal, 26(11): 1429-1436.

[15] Ndjomgoue-Yossa, A.C., Nanseu-Njiki, C.P., Ngameni, E. (2022). Effect of pH on *Escherichia coli* removal by electrocoagulation and elimination kinetics after treatment. Journal of Chemistry, 2022(1): 5249368. https://doi.org/10.1155/2022/5249368

[16] Hamouda, M.A., Anderson, W.B., Van Dyke, M.I., Douglas, I.P., McFadyen, S.D., Huck, P.M. (2016). Scenario-based quantitative microbial risk assessment to evaluate the robustness of a drinking water treatment plant. Water Quality Research Journal of Canada, 51(2): 81-96. https://doi.org/10.2166/wqrjc.2016.034

[17] Fout, G.S., Borchardt, M.A., Kieke Jr, B.A., Karim, M.R. (2017). Human virus and microbial indicator occurrence in public-supply groundwater systems: meta-analysis of 12 international studies. Hydrogeology Journal, 25(4): 903-919. https://doi.org/10.1007/s10040-017-1581-5

[18] Chakraborty, A., Chandran, A., Bhat, K.G. (2015). Does citrus fruit juice have antibacterial effect against enteric pathogenic bacteria. Indian Journal of Applied Research, 5(5): 1-3.

[19] Al-Imara, E.A., Al-Jaryan, R.L., Jawad, S.F., Kareem, M.M., Mubarak, H.A. (2021). Engineered electrocoagulation reactor for the removal of E. coli from wastewaters. IOP Conference Series: Earth and Environmental Science, 877(1): 012048. https://doi.org/10.1088/1755-1315/877/1/012048

[20] Aguilar-Ascon, E. (2019). Removal of *Escherichia coli* from domestic wastewater using electrocoagulation. Journal of Ecological Engineering, 20(5): 42-51. https://doi.org/10.12911/22998993/105331

[21] Silva, B.H., Melo, M.A. (2015). Trihalometanos em água potável e riscos de câncer: Simulação usando potencial de interação e transformações de Bäcklund. Química Nova, 38(3): 309-315. https://doi.org/10.5935/0100-4042.20150013

[22] Abukhanafer, G., Al-Fatlawi, A.H., Joni, H.H. (2021). Effect of pulse electric field on water characteristics as a disinfection function in filtration unit. Engineering and Technology Journal, 39(1): 116-121.

[23] Kadhum, S.T., Alkindi, G.Y., Albayati, T.M. (2022). Remediation of phenolic wastewater implementing nano zerovalent iron as a granular third electrode in an electrochemical reactor. International Journal of Environmental Science and Technology, 19(3): 1383-1392. https://doi.org/10.1007/s13762-021-03205-5

[24] Al-Rubaiey, N.A., Al-Barazanjy, M.G. (2018). Ultrasonic technique in treating wastewater by electrocoagulation. Engineering and Technology Journal,

36(1 Part C): 54-62.
[25] Lynn, W., Heffron, J., Mayer, B.K. (2019). Electrocoagulation as a Pretreatment for Electroxidation of E. coli. Water, 11(12): 2509. https://doi.org/10.3390/w11122509
[26] Ghernaout, D., Badis, A., Kellil, A., Ghernaout, B. (2008). Application of electrocoagulation in *Escherichia coli* culture and two surface waters. Desalination, 219(1-3): 118-125. https://doi.org/10.1016/j.desal.2007.05.010
[27] Barrera-Díaz, C., Martínez-Barrera, G., Gencel, O., Bernal-Martínez, L.A., Brostow, W. (2011). Processed wastewater sludge for improvement of mechanical properties of concretes. Journal of Hazardous Materials, 192(1): 108-115. https://doi.org/10.1016/j.jhazmat.2011.04.103
[28] Alnasrawy, S.T., Alkindi, G.Y., Albayati, T.M. (2021). Removal of high concentration phenol from aqueous solutions by electrochemical technique. Engineering and Technology Journal, 39: 189-195. https://doi.org/10.30684/etj.v39i2A.1705
[29] Pulido, M.E. (2005). Evaluation of an electro-disinfection technology as an alternative to chlorination of municipal wastewater effluents. PhD thesis, Engineering and Applied Science, University of New Orleans.
[30] Ganizadeh, F., Rezaee, A., Godini, H. (2017). Elimination of pathogenic bacteria using electrochemical process containing steel mesh electrode. Journal of Advances in Environmental Health Research, 5(1): 23-28. https://doi.org/10.22102/jaehr.2017.46968
[31] Moneer, A., El Nemr, A. (2012). Electro-coagulation for textile dyes removal. In: Non-Conventional Textile Waste Water Treatment, pp. 161-204.
[32] Bharath, M., Krishna, B.M., Kumar, B.M. (2018). A review of electrocoagulation process for wastewater treatment. International Journal of ChemTech Research, 11(3): 289-302.
[33] Demasure, L. (2017). Reinvent the toilet challenge (The Gates Foundation): Electrochemical Water Sanitation. / Louis Demasure. Master of Science in de bio-Ingenieurswetenschappen: Milieutechnologie.
[34] Harif, T., Adin, A. (2011). Size and structure evolution of kaolin–Al$(OH)_3$ flocs in the electroflocculation process: A study using static light scattering. Water Research, 45(18): 6195-6206. https://doi.org/10.1016/j.watres.2011.09.027
[35] Hashim, K.S. (2017). The innovative use of electrocoagulation-microwave techniques for the removal of pollutants from water. Doctoral Thesis, Liverpool John Moores University.
[36] Hashim, K.S., Ewadh, H.M., Muhsin, A.A., Zubaidi, S.L., Kot, P., Muradov, M., Aljefery, M., Al-Khaddar, R. (2021). Phosphate removal from water using bottom ash: Adsorption performance, coexisting anions and modelling studies. Water Science and Technology, 83(1): 77-89. https://doi.org/10.2166/wst.2020.561
[37] Mubarak, H.A., Kubba, M.A., Hashim, K., Al-Janabi, A., Safaa, K.H. (2021). A short review on dyes removal from water and wastewaters. IOP Conference Series: Materials Science and Engineering, 1184(1): 012017. https://doi.org/10.1088/1757-899X/1184/1/012017
[38] Elias, A.M., Raman, S.J. (2019). Effectiveness of electro chemical disinfection on removal of *Escherichia coli*. International Journal of Emerging Technologies and Innovative Research, 6(5): 431-439.
[39] Castro-Ríos, K., Taborda-Ocampo, G., Torres-Palma, R.A. (2014). Experimental design to measure *Escherichia coli* removal in water through electrocoagulation. International Journal of Electrochemical Science, 9(2): 610-617. https://doi.org/10.1016/S1452-3981(23)07743-X
[40] Boudjema, N., Drouiche, N., Abdi, N., Grib, H., Lounici, H., Pauss, A., Mameri, N. (2014). Treatment of Oued El Harrach river water by electrocoagulation noting the effect of the electric field on microorganisms. Journal of the Taiwan Institute of Chemical Engineers, 45(4): 1564-1570. https://doi.org/10.1016/j.jtice.2013.10.006
[41] Riyanto, Agustiningsih, W.A. (2018). Electrochemical disinfection of coliform and *Escherichia coli* for drinking water treatment by electrolysis method using carbon as an electrode. IOP Conference Series: Materials Science and Engineering, 349(1): 012053. https://doi.org/10.1088/1757-899X/349/1/012053
[42] Hashim, K.S., Ali, S.S.M., AlRifaie, J.K., Kot, P., Shaw, A., Al Khaddar, R., Idowu, I., Gkantou, M. (2020). *Escherichia coli* inactivation using a hybrid ultrasonic–electrocoagulation reactor. Chemosphere, 247: 125868. https://doi.org/10.1016/j.chemosphere.2020.125868
[43] AL-Jaryan, I.L., Al-Jaryan, R.L., Jouda, S.A., Alotaibi, S., Abdellatif, M., AlKhayyat, A. (2021). Removal of bacterial pollution from municipal wastewater using electrocoagulation technique. IOP Conference Series: Materials Science and Engineering, 1058(1): 012024. IOP Publishing. https://doi.org/10.1088/1757-899X/1058/1/012024
[44] Ghernaout, D., Elboughdiri, N., Lajimi, R. (2022). Electrocoagulation of *Escherichia coli* culture: Effects of temperature and cell concentration. Open Access Library Journal, 9(5): 1-23. https://doi.org/10.4236/oalib.1108763
[45] Abdulkareem, F.A., Hussain, T.A., Najaf, A.A.N. (2021). The treatment of wastewater produced from Al-Doura refinery to increase production and minimize pollutant materials. Iraqi Journal of Science, 3984-3996.
[46] Chopra, A.K., Sharma, A.K. (2014). Disinfection of biologically treated municipal wastewater using electrochemical process. Separation Science and Technology, 49(17): 2613-2619. https://doi.org/10.1080/01496395.2014.937815
[47] Khandegar, V., Saroha, A.K. (2013). Electrocoagulation for the treatment of textile industry effluent–A review. Journal of Environmental Management, 128: 949-963. https://doi.org/10.1016/j.jenvman.2013.06.043
[48] Boinpally, S., Kolla, A., Kainthola, J., Kodali, R., Vemuri, J. (2023). A state-of-the-art review of the electrocoagulation technology for wastewater treatment. Water Cycle, 4: 26-36. https://doi.org/10.1016/j.watcyc.2023.01.001
[49] Anuf, A.R., Ramaraj, K., Sivasankarapillai, V.S., Dhanusuraman, R., Maran, J.P., Rajeshkumar, G., Rahdar, A., Díez-Pascual, A.M. (2022). Optimization of electrocoagulation process for treatment of rice mill effluent using response surface methodology. Journal of Water Process Engineering, 49: 103074. https://doi.org/10.1016/j.jwpe.2022.103074
[50] Delaire, C., van Genuchten, C.M., Amrose, S.E., Gadgil, A.J. (2016). Bacteria attenuation by iron electrocoagulation governed by interactions between

bacterial phosphate groups and Fe (III) precipitates. Water Research, 103: 74-82. https://doi.org/10.1016/j.watres.2016.07.020

[51] Zimmermann, U., Schulz, J., Pilwat, G. (1973). Transcellular ion flow in *Escherichia coli* B and electrical sizing of bacterias. Biophysical Journal, 13(10): 1005-1013. https://doi.org/10.1016/S0006-3495(73)86041-2

[52] Lekhlif, B., Oudrhiri, L., Zidane, F., Drogui, P., Blais, J.F. (2014). Study of the electrocoagulation of electroplating industry wastewaters charged by nickel (II) and chromium (VI). J. Mater. Environ. Sci, 5(1): 111-120.

[53] Gusa, R.F., Sari, D.N., Afriani, F., Sunanda, W., Tiandho, Y. (2020). Effect of electrode numbers in electrocoagulation of Batik Cual wastewater: Analysis on water quality and energy used. IOP Conference Series: Earth and Environmental Science, 599(1): 012061. https://doi.org/10.1088/1755-1315/599/1/012061