Journal of The Electrochemical Society, 2025 **172** 043504
1945-7111/2025/172(4)/043504/13/$40.00

Effective Elimination of Pollutants from Wastewater through a Combination Aerated-Photo-Electrocoagulation Technique: Investigation on Operational Parameters

Perumal Asaithambi,[1,z] Abdelrahman O. Ezzat,[2,z] Omar H. Abd-Elkader,[3] Arun Thirumurugan,[4] Hamad A. Al-Lohedan,[2] and Sivakumar Vigneshwaran[5]

[1]*Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Jimma, Ethiopia*
[2]*Department of Chemistry, College of Sciences, King Saud University, Riyadh 11451, Saudi Arabia*
[3]*Department of Physics and Astronomy, College of Sciences, King Saud University, Riyadh 11451, Saudi Arabia*
[4]*Sede Vallenar, Universidad de Atacama, Vallenar-1612178, Chile*
[5]*Key Laboratory of Advanced Materials of Tropical Island Resources, Ministry of Education, School of Chemistry and Chemical Engineering, Hainan University, Haikou 570228, People's Republic of China*

Electrocoagulation (EleC) can be combined with other processes to improve water and wastewater pollutant removal. EleC exhibits enhanced performance when combined with advanced oxidation processes (AOPs). The reduction of color and COD in LLW was examined using an aerated, photo (UV), aerated+UV, EleC, aerated+EleC, UV+EleC, and aerated+UV+EleC methods. Experimental results showed that at the following parameters: treatment duration (TD) = 75 min, pH = 7, aerated flow rate (AFR) = 60 l min^{-1}, UV power = 32 W, current density (J) = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, and electrode pair (EleP) = Fe/Fe, the aerated+UV+EleC method eliminated nearly 100% of color and 95.50% of COD from LLW with an electrical energy consumption of 7.70 kWh m^{-3}. Compared to results from aerated, UV, aerated/UV, EleC, aerated/EC, and UV/EleC procedures, the values discovered were substantially higher. In order to ascertain the most favorable circumstances for operation, the impact of a number of different control factors, including TD: 15–90 min, AFR: 10–60 l min^{-1}, UV power: 8–32 W, J: 0.1–0.60 A dm^{-2}, CODs: 1250–6250 mg l^{-1}, pH: 1–11, GBE: 1–5 cm, and EleP: Al/Al, Al/Fe, Fe/Al, Fe/Fe on color and COD reduction was investigated. The results demonstrated that LLW was effectively treated using aerated+UV+EleC treatment combination.
 [DOI: 10.1149/1945-7111/adc76b]

Manuscript submitted January 9, 2025; revised manuscript received March 21, 2025. Published April 9, 2025.

The rise in global population and emerging consumption patterns have led to significant waste production, which is predominantly disposed of in sanitary landfills.[1] The leachate that is produced by sanitary landfills has the potential to generate a number of contaminants, including organic and inorganic compounds. Some of these chemicals are refractory, poisonous, and include heavy metals, etc.[2,3] Because of its intricate composition and the fact that it is resistant to degradation, leachate waste from sanitary landfills is regarded to be a significant source of pollutants.[4] The release of landfill leachate wastewater (LLW) into the environment adversely impacts aquatic life, diminishes soil fertility, produces carcinogenic consequences in humans, and ultimately disrupts ecological equilibrium.[5,6] The LLW has a highly variable composition and a high pollutant load, making it exceedingly challenging to remove pollutants to a standard level.[7] For this reason, it is essential to discover a method that is efficient in removing pollutants from wastewater solutions. Prior research has established many methodologies for the elimination of pollutants from LLW, including coagulation-flocculation,[8] ozone (O_3)/Fenton,[9] combination of electrocoagulation (EleC)[10–12] with advanced oxidation processes (AOPs),[13,14] electrooxidation,[15] electro–Fenton,[3] ultrasound (US) irradiation,[16] photo(UV)–Fenton, UV–H_2O_2 and Fenton reaction,[4] Fenton and O_3 systems,[5] etc. Despite the effectiveness of some of those methods, their widespread use in practice is constrained by a number of drawbacks, including comparatively higher operating costs, the need for additional chemicals, and complicated treatment conditions.

The EleC approach typically employs metals, such as iron (Fe) or aluminum (Al), as sacrificial anodes, resulting in the release of metal ions when current is applied between the anodes and cathodes.[17,18,19] The ions experienced hydrolysis, resulting in the formation of metal hydroxide and complexes, while contaminants in the solution were removed by adsorption, neutralization, and co-precipitation.[17,18,19] As a result, the EleC method, which is straightforward, effective, and economical, is well-suited for the treatment of wastewater.[17,18,20] The primary EleC reactors employed in laboratory and industrial settings consist of tanks with integrated electrodes, which do not come into touch with coagulants or pollutant particles. The mechanical mixer is therefore utilized in order to improve the efficiency of the mixing process. Nevertheless, the high shear force induced by mechanical agitation might result in the permanent disintegration of flocs and contribute to increased energy consumption.[21]

The efficacy of EleC in conjunction with additional treatments has been successfully shown by an extensive number of research investigations, including aerated–EleC,[22,23] EleC/Chemical coagulation, continuous-flow EleC reactor and UV–electro–Fenton,[24] EleC/Adsorption, EleC/Magnetic field, EleC/reverse osmosis,[25] alternating–current EleC,[26,27] peroxi–EleC,[28] biological treatment with EleC,[29] O_3 assisted EleC,[30–33] UV–EleC,[34–36] US/EleC,[33,37,38] EleC–nanofiltration and membrane filtration[39–41] for the elimination of contaminants from wastewater.

As a result, some researchers began combining EleC with airlift reactors to develop airlift–electrocoagulation (AL-EleC) reactors, which were highly effective in removing dye, oil, fluorine, arsenic, and COD from wastewater.[22,42,43] The incorporation of air was yet another factor that contributed to the successful performance of AL–EleC process. One of the benefits of aeration was that it reduced the amount of passivation that occurred on the electrodes and improved the oxidation process.[23] Aeration in the EleC process has been shown to improve the decolorization and COD elimination effectiveness of dye wastewater, as well as the arsenic removal efficiency of contaminated groundwater.[22]

According to Jallouli et al.,[44] tannery effluent COD can be effectively reduced by using sequential EleC and UV treatment procedures. Their findings showed that the combination approach reduced COD by 94.10%, while the reductions from the EleC and UV treatments alone were 85.7% and 55.9%, respectively. Moradi and Moussavi[36] employed an EleC technique alongside a UVC/VUV photo reactor to eliminate COD, total chromium (Cr(III) and Cr(VI)), and sulfide from tannery effluent. According to the findings, the pollutant removal efficiency for acidic and neutral pH solutions were determined to be 99.52%, 100%, 100%, and 98.27%, respectively. Cotillas et al.[45]

[z]E-mail: asaithambi.perumal@ju.edu.et; aezzat@ksu.edu.sa

shown a synergistic impact in the decrease of turbidity and disinfection rate when utilizing UV–EleC method at low current densities. They also found that using UV light enhances output.

Suitable efficiency has been established using aerated and modified electrical coagulation techniques.[46] Numerous publications have shown that EleC with aeration is more successful than EleC without aeration in the elimination of chemical oxygen demand (COD).[2,42] Utilizing an aeration method for the elimination of pollutants from wastewater, the following mechanism was involved such bubble formation, stability and suspension and enhanced gas exchange. Higher removal efficiency was seen in one research when aerated EleC was used to remove COD, oil, and grease from carwash effluents.[47] Niloufar Karimi et al., found that the combination approach of aerated–EleC and maghemite nanoparticle adsorption performed well in eliminating COD from textile wastewater.[42] According to N K Anuar et al., the aeration process can improve the effectiveness of removing NH_3–N and color from leachate waste during EleC.[48] Rusdianasari et al. treated the leachate by combining the EleC and aeration methods with the addition of NaCl, and they presented their results. When a NaCl environment was added, the EleC process with the aeration process worked well.[49] Omar Khalifa et al. used an Al anode in EleC aerated and non–aerated processes to treat synthetic oily wastewater. According to their findings, aerated cells had a removal efficiency that was around 12% higher than that of non–aerated cells.[43]

Our comprehensive review of the literature revealed that combined approaches employing electrochemical (EC) processes and AOPs were effective in eliminating contaminants from synthetic wastewater The utilization of hybrid EC and AOPs for the treatment of real wastewater has been the focus of a limited number of investigations.[50,51] The consumption of electrical energy (CEE) of the integrated techniques is essential from an economic standpoint, with the elimination of contaminants from wastewater. Furthermore, in order to overcome the drawbacks of traditional treatment methods, environmental engineers must design and construct straightforward, effective, and affordable hybrid processes.

As far as the authors are aware, no previous studies have investigated the integration of aeration and UV treatment with an EleC approach for evaluating the CEE associated with color and COD elimination from LLW. This research was conducted with the intention of developing and improving innovative treatment techniques for assessing CEE while simultaneously eliminating pollutants from LLW. The primary goal of this research is to compare aerated, photo (UV), aerated+UV, electrocoagulation (EleC), UV+EleC, aerated+EleC, and aerated+UV+EleC technologies in terms of color and COD elimination, as well as to calculate the CEE from LLW and select the best one. The influence of process factors such as treatment duration (TD), aerated flow rate (AFR), photo (UV) power, current density (J), COD, pH, electrode gap and pair on the COD elimination and CEE of LLW treated with an aerated+UV +EleC process was studied. In addition to this, the synergy index (SI) between the aeration and UV/EleC processes was examined and documented.

Material and Methods

Collection and characterization of wastewater.—Landfill leachate wastewater (LLW) from a municipal solid waste sanitary landfill site in Jimma, Ethiopia, was collected using a clean plastic sample container. The wastewater was then promptly transported to

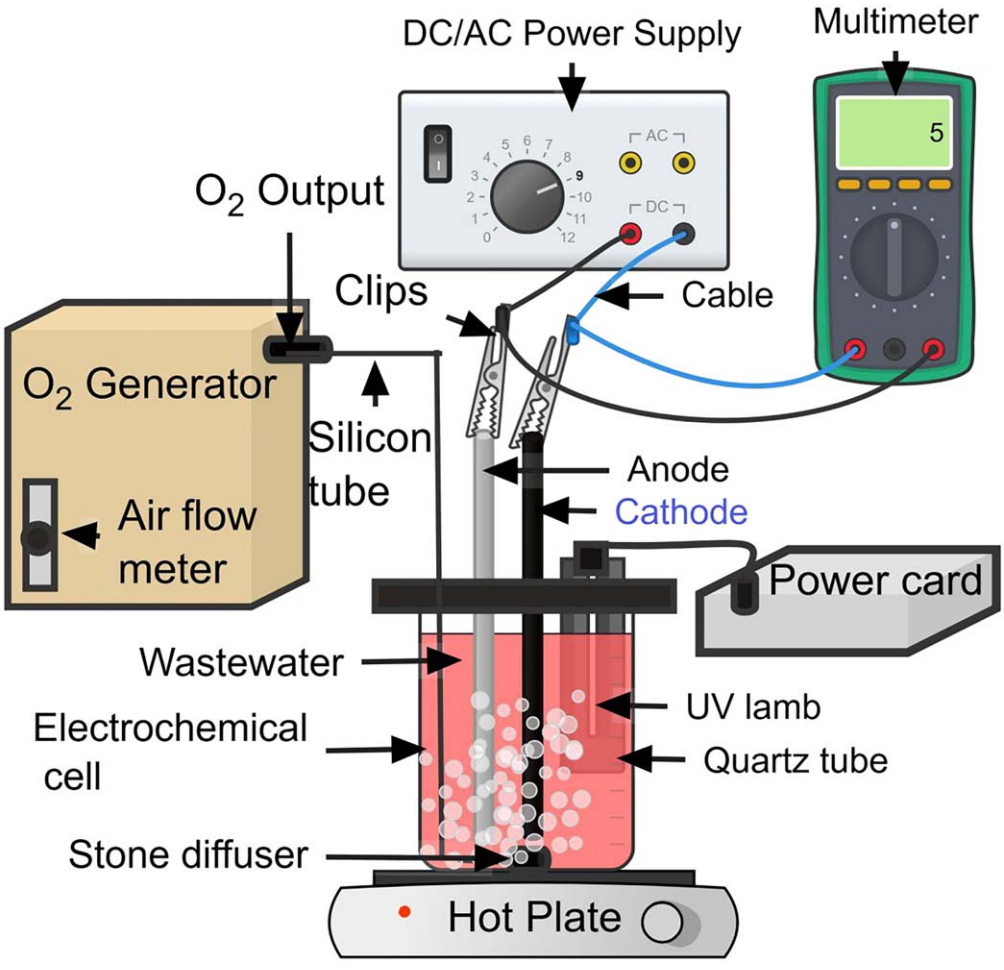


Figure 1. Experimental configuration for the combined Aerated/UV/EleC process.

the laboratory and kept appropriately until it was needed again. The wastewater has the following characteristics: pH: 8.3–8.5, Odor: stench ammonia, temperature: 27 °C–31 °C, color: bright brown, BOD: 2600–3000 mg l^{-1}, COD: 4750–6250 mg l^{-1}, Turbidity: 275–325 NTU, and TSS: 135–175 mg l^{-1}.

Materials and chemicals.—All of the chemical reagents used in the investigations, including NaOH, hexamethylene tetra amine ($(CH_2)_6N_4$), $K_2Cr_2O_7$, HCl, $(NH_4)_2Fe(SO_4)_2$), KI, and etc, were obtained from Merck analytical supplies, and the commercially available version was used without being purified.

Hybrid aerated–photo–electrocoagulation (Aerated+UV+EleC) setup and process.—Figure 1 presents a schematic representation of the aerated+UV+EleC reactor that was utilized for the purpose of this investigation. Perpexi glass was used to build the 1100 ml electrochemical setup with the active working volume of wastewater being 1.0 l. The range of the LLW COD was 1250–6250 mg l^{-1}. Using a dilution factor, distilled water was added to the raw LLW to achieve the required COD concentration. It also comprised an oxygen generator, airflow meter, and stone diffuser. Within the cell, two metal plate electrodes, composed of either aluminum (Al) or iron (Fe), were arranged vertically. Each electrode had a thickness of 0.1 cm and an effective surface area (width x height) of 10 cm by 15 cm, and the spacing between the electrodes was varied between 1 and 5 cm. The electrodes were connected to a DC power supply unit (0–5 A, 0–250 V, 50 Hz; AMETEK Model:EC 1000S) in monopolar parallel mode. Before each run, the electrodes were sandpaper–-polished and rinsed with distilled water and 1% HCl solution to remove the oxides film.

Using a pH meter (Elico: Model LI120), the pH of wastewater was measured and then adjusted to predetermined values using a diluted solution of 0.1 N HCl or NaOH. The specified air flow rate (AFR) was established on the air flow meter valve (aeration does not occur when the AFR is set to 0 l min^{-1}). After a few minutes, when the steady condition was reached, the power supply was turned on, with the correct current and voltage settings. The concentrations of dissolved oxygen (DO) were measured using a multi–parameter water quality analyzer (PCD, OAKTON) that was equipped with a DO electrode (9500 DO_2 meter, JENWAY).

The experiment was conducted under comparable operating circumstances as the aerated–EleC process, however, the reaction contents were further exposed to ultraviolet (UV) radiation. An 8–32 watt low–pressure Mercury lamp with a primary emission wavelength of 254 nm was utilized as the UV light source. The technique is called aerated+UV+EleC (Fig. 1) because the UV light was integrated into the Aerated+EleC process. The aerated+UV+EleC equipment was put on a hot plate so that it could maintain a consistent temperature during the experiment. A multimeter is used to track the current and cell voltage during the EleC, aerated+EleC, UV+EleC, and aerated+UV+EleC processes. In order to quench the reaction, samples were collected from the aerated+UV+EleC reactor at regular intervals and transferred to an Erlenmeyer flask containing $Na_2S_2O_3$ solution. Following a 10 min centrifugation of the samples at 15,000 rpm to separate the liquid from the particles, the liquid supernatant is promptly tested for color (Spectroquant Pharo ®300) and COD (Spectroquant ® TR320).

Analysis.— *COD and color elimination efficiency, (%).*— Equations 1 and 2 is utilized to ascertain the proportion of COD and color elimination in the solution.

$$COD\ \ elimination,\ (\%) = \left(1 - \frac{COD_2}{COD_1}\right) * 100 \qquad [1]$$

Where,

The COD at starting and treatment duration (t) is denoted by COD_1 and COD_2, respectively.

$$\text{Color elimination, } (\%) = \left(1 - \frac{A_2}{A_1}\right) * 100 \qquad [2]$$

Where,

The absorbance spectrum areas under the curves before and after treatment time t are denoted by A_1 and A_2, respectively.

Consumption of electrical energy (CEE).—This hybrid process is energy–intensive due to the combination of aerated and UV with the EleC technique. Electrical energy consumption may represent a significant operating cost.[52] Thus, electrical energy consumption may be used to assess the hybrid process's economic feasibility. Therefore, the following Eqs. 3–5 was used to determine the total quantity of electrical energy consumed ($CEE_{Aerated/UV/EleC}$).[53]

$$CEE_{Aerated/UV/EleC} = CEE_{Aerated} + CEE_{UV} + CEE_{EleC} \qquad [3]$$

Where,

$CEE_{Aerated/UV/EleC}$, $CEE_{Aerated}$, CEE_{UV}, CEE_{EleC} are consumed electrical energy for aerated–UV–EleC process, aerated, UV and EleC process, respectively.

EleC

$$CEE_{EleC} = \frac{UIt}{V_R},\ (\text{kWhr/m}^3) \qquad [4]$$

Where,

The variables U, I, t, and V_R represent cell voltage (V), applied current (A), treatment duration (min), and wastewater volume (L), respectively.

Aerated plus UV

$$CEE_{Aerated} + CEE_{UV} = \frac{P_{Aerated+UV} * t * 1000}{V_R * 60 * \log\left(\frac{COD_2}{COD_1}\right)},\ \text{kWhr/m}^3 \qquad [5]$$

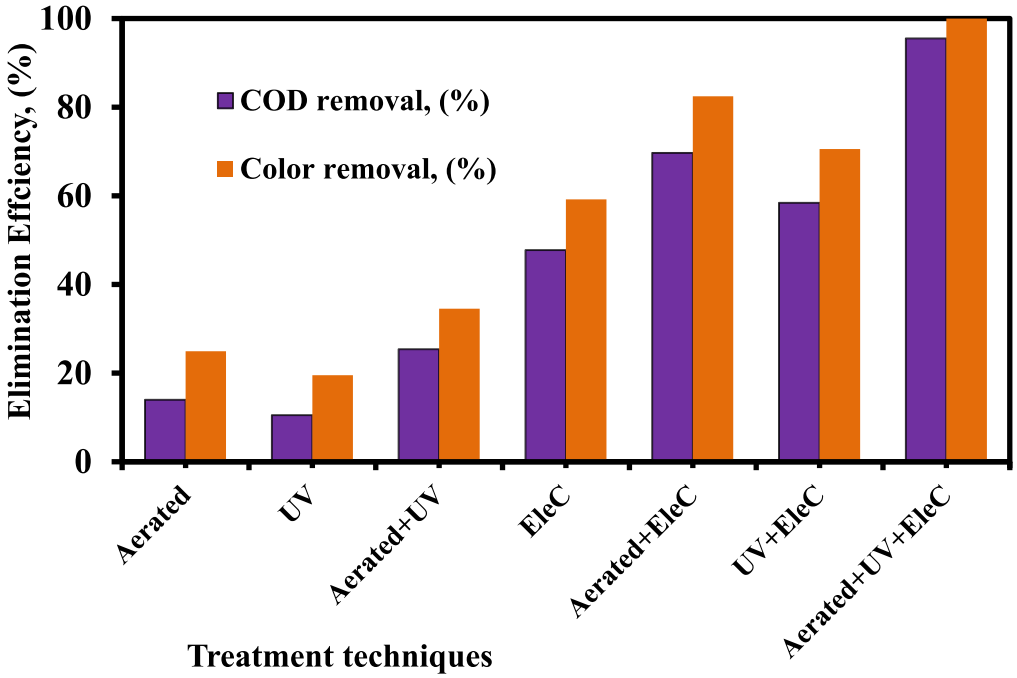
Where,

$P_{Aerated+UV}$–rated power for the UV plus aerated process, respectively, is expressed in kW.

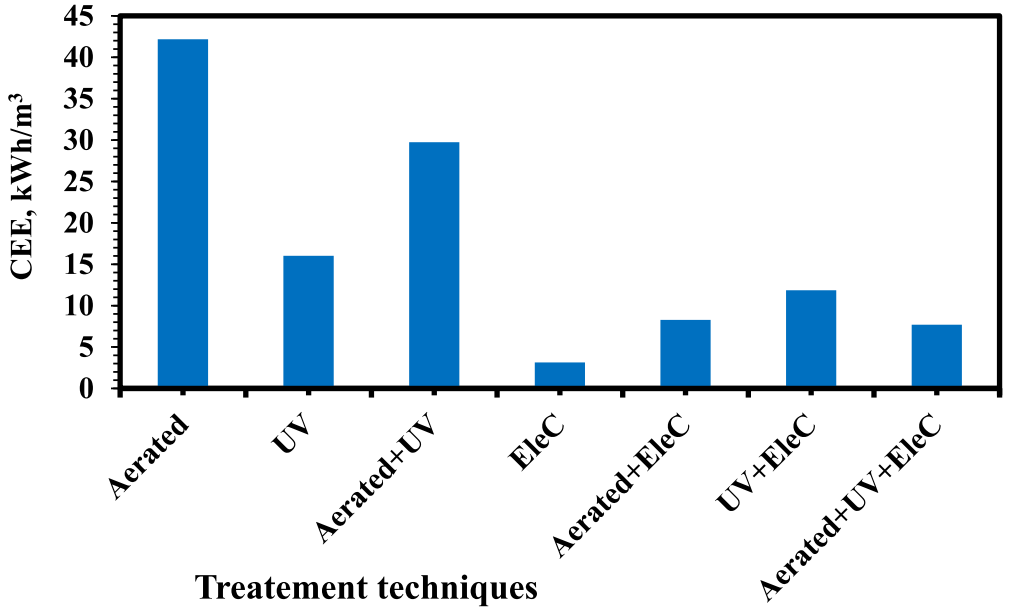
Results and Discussion

The comparison of processes.—In this particular region, investigations were conducted out in order to compare the required CEE with the % with which color and COD were removed. Wastewater from LLW was treated using the separate techniques of aerated, UV, and EleC as well as several combinations of aerated, UV, and EleC procedures, including aerated/UV, aerated+EleC, UV+EleC, and aerated+UV+EleC. The findings are presented in Figs. 2a and 2b. Figure 2a shows that when advanced oxidation and electrochemical processes are used to eliminate color and COD from LLW, the rankings are as follows: color and COD elimination of UV < aerated < aerated+UV < EleC < UV+EleC < aerated+EleC < Aerated +UV+EleC. Figure 2a made it clear that the Aerated+UV+EleC, UV+EleC, aerated+EleC, and EleC only processes had much greater % of color and COD removal efficiency than the UV and aerated only, and aerated+UV processes.

According to the aforementioned results, color and COD removal percentages significantly improved when aerated/UV was added to the EleC process. The outcomes demonstrated that a single technique, such as UV, aerated, and EleC, was insufficient to remove all color and COD. In comparison to individual processes, the combination of other processes, such as aerated/EleC, UV/EleC, and aerated+UV+EleC, is more effective. The successful elimination of color and COD from LLW may result from the formation of parallel pathways that generate sufficient ·OH radicals through aeration, UV and EleC activities.[54–59] In conclusion, the system's simultaneous aeration, UV, and EleC processes may have contributed to the color and COD elimination. By employing an aeration



(a)



(b)

Figure 2. Evaluation of aerated only, UV, aerated/UV, EleC, aerated/EC, UV/EleC, and aerated/UV/EleC method on the (a) COD, and color elimination (%), and (b) CEE from wastewater (Conditions of the experiment: treatment duration (TD) = 75 min, aerated flow rate (AFR) = 60 l min^{-1}, photo (UV) power = 32 W, current density (J in A dm^{-2}) = 0.50, COD = 2500 mg l^{-1}, pH = 7, gap between electrodes (GBE) = 1 cm, and electrode pair (EleP) = Fe/Fe).

technique, the following mechanism was involved, (i) Bubble formation: Oxygen is introduced into wastewater, causing bubbles that increase oxygen levels. (ii) Stability and suspension: Nano bubbles remain suspended due to their high surface tension. Allowing extended interaction with contaminates. (iii) Enhanced gas exchange: Their high surface area-to-volume ratio optimizes oxygen transfer, supporting the degradation of pollutant from wastewater.

$$Wastewater + microorganisms + O_2 \rightarrow CO_2 + H_2O + microorganisms + energy \quad [6]$$

The aeration in the EleC reactor accelerates the oxidation reaction at the anode, hence augmenting the production of Fe^{2+} ions, which facilitates the production of $Fe(OH)_{3(s)}$ flocs.[60] The increases in reaction time enhance the production of hydroxide ions from the cathode.[61] Consequently, the removal of contaminants

occurred continuously with prolonged reaction time, attributed to enhanced interaction between the metal hydroxide flocs and the contaminants.[46]

Reaction at anode:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-} \quad E^0 = -0.44 \text{ V vs } SHE \qquad [7]$$

Reaction at cathode:

$$2H_2O_{(l)} + 2e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq)} \quad E^0 = 0.83 \text{ V vs } SHE \qquad [8]$$

Reaction at overall:

$$Fe_{(s)} + 2H_2O_{(l)} \rightarrow Fe(OH)_{2(s)} + H_{2(g)} \qquad [9]$$

The dissolved Fe^{2+} oxidizes to become insoluble $Fe(OH)_3$ in the presence of oxygen.

$$4Fe^{2+}_{(aq)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4\ Fe(OH)_{3(s)} + 8H^{+}_{(aq)} \qquad [10]$$

The *Fe(OH)n(s)* that persist in the aqueous stream as a gelatinous suspension can eliminate pollutants from the wastewater by complexation or electrostatic attraction followed by coagulation.

Moreover, supplementary UV irradiation was employed during the EleC process. There was an increase in the number of photoactive sites that were available, which meant that the EleC process was benefitted.

Table I displays the findings of a comparison of the pollutant removal efficiency attained by combining the UV+EleC and aerated +EleC procedures with different kinds of wastewater. According to the results, the combined aerated+EleC and UV+EleC procedure is more effective at eliminating contaminants from all kinds of wastewater (Table I). However, there is a lack of study on the removal of pollutants and the computation of the amount of electrical energy that is used by LLW through the utilization of a hybrid Aerated+UV +EleC approach.

The economic feasibility of combining an EleC with an aerated and UV process is influenced by the consumption of electrical energy. The Eqs. 3–5 was used to do the calculation, and the findings are shown in Fig. 2b. Using a hybrid Aerated+UV+EleC method, it was necessary to consume 7.7 kWhr m^{-3} of electrical energy in order to totally remove color (100%) and COD (95.50%) from the leachate effluent from the landfill. When compared to the aerated +UV+EleC, other combinations and individual operations, such as aerated/UV, UV/EleC, aerated/EleC, and EleC, aerated, UV process, needed a higher amount of electrical energy usage in order to eliminate better % of color and COD. As a result, this hybrid method (aerated+UV+EleC) based on AOPs and electrochemical processes are suitable for treating wastewater and industrial effluents.

Process optimization for aerated+UV+EleC.—In order to improve the performance of the aerated+UV+EleC process, the following factors were investigated and addressed in detail: treatment duration (TD): 15–90 min; aerated flow rate (AFR): 10–60 l min^{-1}; current density (J): 0.1–0.60 A dm^{-2}; UV power: 8–32 W; COD: 1250–6250 mg l^{-1}; pH: 1–1; electrode gap: 1–5 cm; and electrode pair: Al/Al, Al/Fe, Fe/Al, and Fe/Fe.

Influence of TD.—When it comes to employing a hybrid method to treat industrial wastewater, the amount of time that will be spent on the treatment process is one of the most significant aspects to take into consideration.[66,67] The outcomes of the procedure of aerated +UV+EleC using the AFR = 60 l min^{-1}, pH = 7, UV power = 32 W, COD = 2500 mg l^{-1}, J = 0.50 A dm^{-2}, GBE = 1 cm, and EleP= Fe/Fe are shown in Fig. 3. As shown in Fig. 3, the % of color and COD elimination, as well as CEE, has grown from 49 to 100%, 40 to 100%, and 1.7 to 10.5 kWhr m^{-3}, respectively, as the TD has increased from 15 to 90 min. Garca-Morales et al., have presented findings that are in agreement with these findings.[68] A direct association exists between the quantity of ions produced by the electrodes and the extent of color and COD removal from the water. As the duration of treatment extends, an increased amount of electrode ions and associated oxidizing species is generated.[63,66] Consequently, with an extended treatment period, the efficacy in removing color and COD improves. Increasing the cell voltage enhances the generation of ·OH radicals, hence improving color and COD removal.[67]

Impact of AFR.—The tests assessed the impact of the air flow rate (AFR) on color and COD elimination efficiency by altering the AFR from 10 to 60 l min^{-1}, while maintaining other operational parameters constant (TD = 75 min, pH = 7, COD = 2500 mg l^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, GBE = 1 cm, and EleP= Fe/Fe). When compared to a non-aeration process, it has been shown that aeration enhances color and COD elimination efficiency.[22,42] An appropriately increased AFR can significantly improve the efficiency of COD and color elimination (Fig. 4). Turbulence produced by the increasing air flow enhanced the mixing conditions of the solutions, raised the probability that the pollutants and flocs would collide, and improved the efficiency of the pollutants' collection. Additionally, the turbulence improved the movement of ions between the electrodes by reducing the passivation layer on the electrodes. At the same time, the electrode surfaces developed metalhydroxide flocs and the released gases accumulated, which increased the electrical resistance between the electrodes, causing poor performance and additional energy consumption during the EleC process. The air flow enhanced flow velocity, enhancing hydrodynamic scouring, while reducing the influence of air bubbles and deposits. Simultaneously, an increased AFR can increase the generation of specific reactive oxygen species accelerates pollutant breakdown and enhances efficiency.[69]

The reduction in eliminate rate at high airflow conditions may be ascribed to excessive aeration disrupting the aggregated flocs, resulting in the release of contaminants absorbed during the EleC process back into the solutions. This also resulted in a rise in the concentration of suspended solids. In instances of diminished or absent AFR, the restricted oxidation rate of Fe^{3+} ions may lead to poor color and COD elimination efficiency.

Influence of UV power.—An extra UV exposure was carried out while the aerated plus EleC procedure was being carried out. In a 90 min aerated+UV+EleC process for LLW, UV–C lamps were used to study a UV power range of 8 to 32 W, as shown in Fig. 5. Increased the intensity of the UV light from 8 to 32 Watts, which led to an increase in the COD elimination efficiency and CEE from 55.50 to 95.50% and 4.90 to 7.70 kWh m^{-3}, respectively. This was accomplished by increasing the power of the UV light. These results concur with those published by Keramati et al.[70] Variations in lamp power and the amount of light source irradiation per unit area have an impact on the generation of additional ·OH radicals.[70] The aerated +UV+EleC performance was positively impacted by the photoactive areas improved accessibility. This improvement was brought about by an increase in the production of OH radicals through the processes of photo–decomposition and photo–reduction.[71]

$$Fe(OH)^{2+} + hv \rightarrow Fe^{2+} + \cdot OH \qquad [11]$$

$$R(CO_2) - Fe^{3+} + hv \rightarrow R(\cdot CO_2) + Fe^{2+} \rightarrow \cdot R + CO_2 \qquad [12]$$

For this reason, the aerated/UV/EleC approach for LLW is more efficient than other methods in terms of removing color and COD while also making use of electrical energy.

Influence of J.—Applied current density (J) is defined as the ratio of the amount of current that is applied to the area of the electrode. This is a crucial parameter that affects the hybrid EleC process, since it dictates the amount of metal dissolved in solutions, which in turn

Table I. Aerated plus EleC and UV plus EleC methods for pollutant removal from various types of wastewater.

Treatment processes	Wastewater types	Experimental conditions	Removal efficiency,	References
UV-EleC-oxidation	Gold processing plant	pH=10, current density = 15 mA cm^{-2}, cathodes = graphite–Al and anodes = SS, treatment time = 60 min	CN = 100% Ni = 73%, Cu = 100% and Zn = 78.8%	62
EC combined to UVC/ VUV	Tannery	Treatment time = 60 min, volume = 180 ml, initial [S^{2-}] = 50 mg l^{-1}, electrodes = Al, inter–electrode distance = 1 cm, current = 500 mA	COD = 99.52% chromium = 100% Sulphide = 98.27%	36
EC+UV	Tannery	COD = 7375.68 mgl^{-1}, applied voltage = 5 V; current density = 12 A cm^{-2}, Treatment time = 8 hr	COD = 94.10%	44
UV+EC	Distillery	current density = 0.175 A dm^{-2}, COD = 3600 mg l^{-1}, UV = 32 W, electrode combination = Fe/Fe, inter–electrode distance = 0.75 cm, pH = 7, and reaction time = 4 h	Color = 72.45% COD = 60.68%	63
UV+EleC	Simulate synthetic effluent	Electric current = 300 mA, pH = 10, treatment time = 60 min, electrodes = Fe-SS, distance between electrodes = 5 cm, H_2O_2 = 4 mg l^{-1}	Nickel = 85%, cyanide = 96%, zinc =94%, and copper = 98%	64
Aerated-EleC	Municipal stabilized landfill leachate	Current density = 30 m Acm^{-2}, electrolysis time = 60 min and pH = 7.3.	NH_4–N = 25.6%, TN = 23.67%, COD =25.6% and TOC =28.7%	61
Aerated+EC	Oily	Conductivity = 1780 ± 11 μS cm^{-1}. initial pH = 3.8, current density =120 A m^{-2}	COD =93.3%	43
Aerated+EC	Automobile wash	Distance among the electrodes = 5 cm, reaction time = 40 min, pH = 6; current density = 25 A m^{-2} with stirring speed = 200 rpm.	COD = 95.1% oil & grease = 92.5	47
Aerated-EleC	Oily	Current density = 120 A m^{-2}, COD = 164.2 ± 2.1 mg l^{-1}, pH = 3.8.	COD = 93.3%	43
Aerated continuous EleC	River water	HRT = 12 min, electrode spacing = 2 cm, 9 V, electrode = Al–Al	COD = 61.4% TCL 71.5%	65
UV+EleC	Landfill leachate	TD = 75 min, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP= Fe/Fe	Color=70.57% COD=58.44%	This study
Aerated+EleC	Landfill leachate	TD = 75 min, AFR = 60 l min^{-1}, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP= Fe/Fe	Color=82.45% COD=69.68%	This study
Aerated +UV+EleC	Landfill leachate	TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP= Fe/Fe	Color=100% COD=95.50%	This study

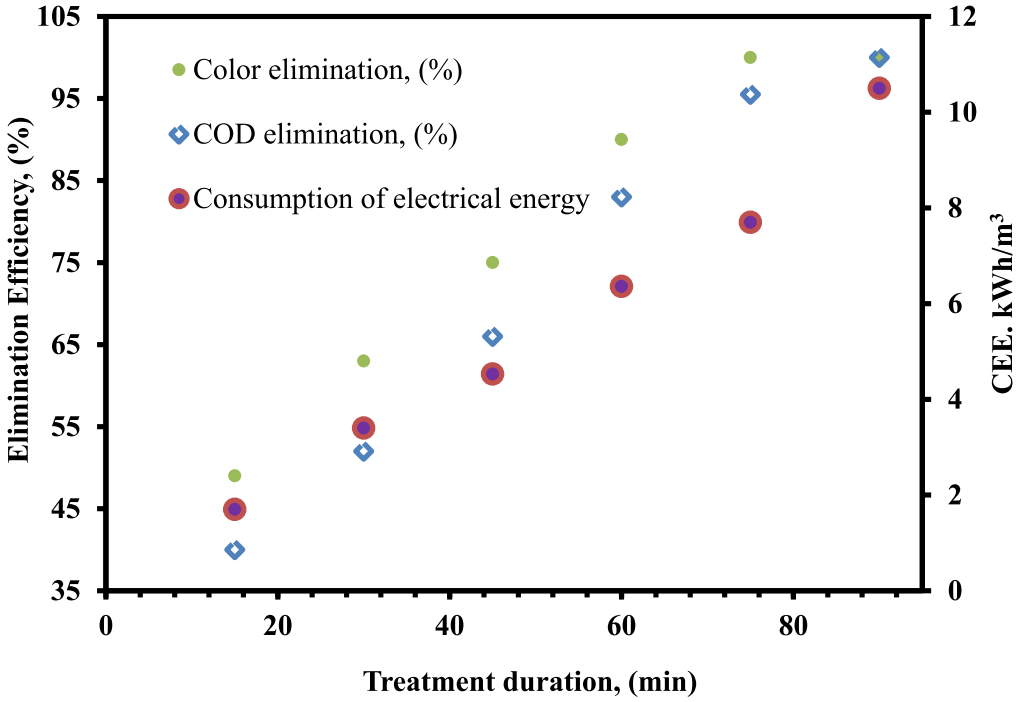


Figure 3. Impact of TD on % COD, and color elimination, and CEE from wastewater by combined aerated/UV/EleC method (Conditions of the experiment: AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP = Fe/Fe).

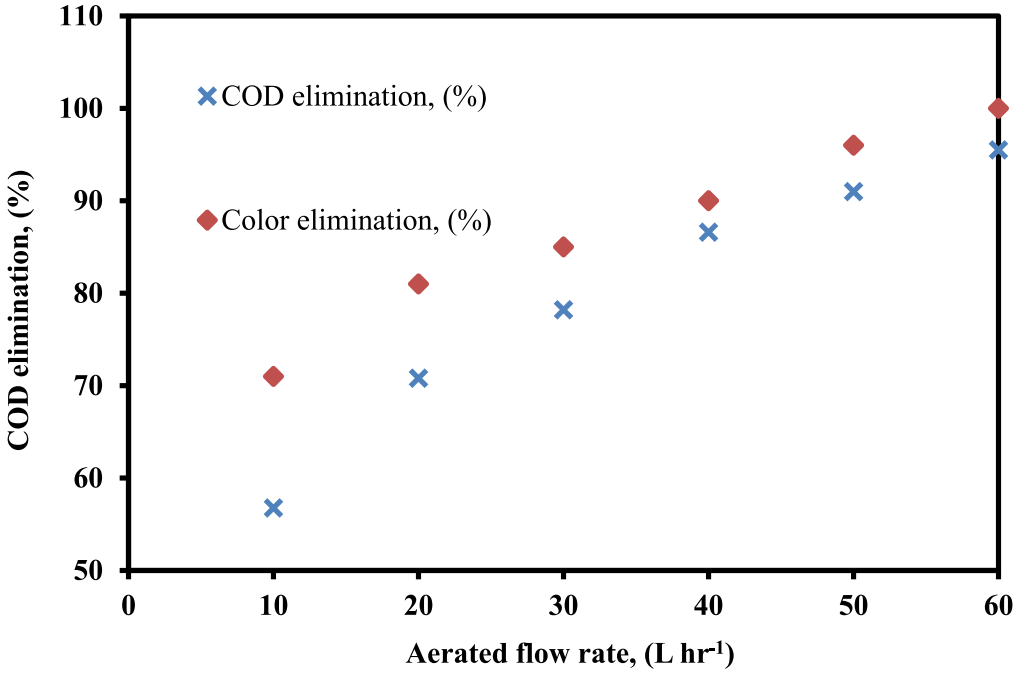


Figure 4. Impact of AFR on the (%) COD, and (%) color elimination from LLW by combined aerated/UV/EleC approach (Experimental conditions of the: TD = 75 min, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP = Fe/Fe).

influences the formation of coagulants.[72,73] Figure 6 illustrated the COD removal rate with time in the aerated+UV+EleC reactor at varying J (ranging from 0.1 to 0.6 A dm^{-2}). The findings indicated that the COD elimination rate augmented with increasing J, as elevating the J from 0.1 to 0.6 A dm^{-2} enhanced the removal efficiency from 33.70 to 100%. Faraday's Law states that increasing the current will yield a greater production of metals and hydroxyl, facilitating the formation of coagulants and the removal of contaminants. This would also produce additional H_2 bubbles from the cathode that sequester contaminants, enhancing solution mixing and mass transfer in proximity to the electrode. Increased active species generated by the anode would enhance the chemical oxidation reaction; nevertheless, some studies have observed that this may result in a rise in by–products and elevated environmental concerns. Excessive applied current may result in electrode passivation and heightened polarization, thereby increasing electrical energy consumption.[74]

The calculated quantity of CEE for 75 min of treatment at varying J is illustrated in Fig. 6. It shown that CEE increased from 0.85 to 10.13 kWh m^{-3} when the J increased from 0.1 to

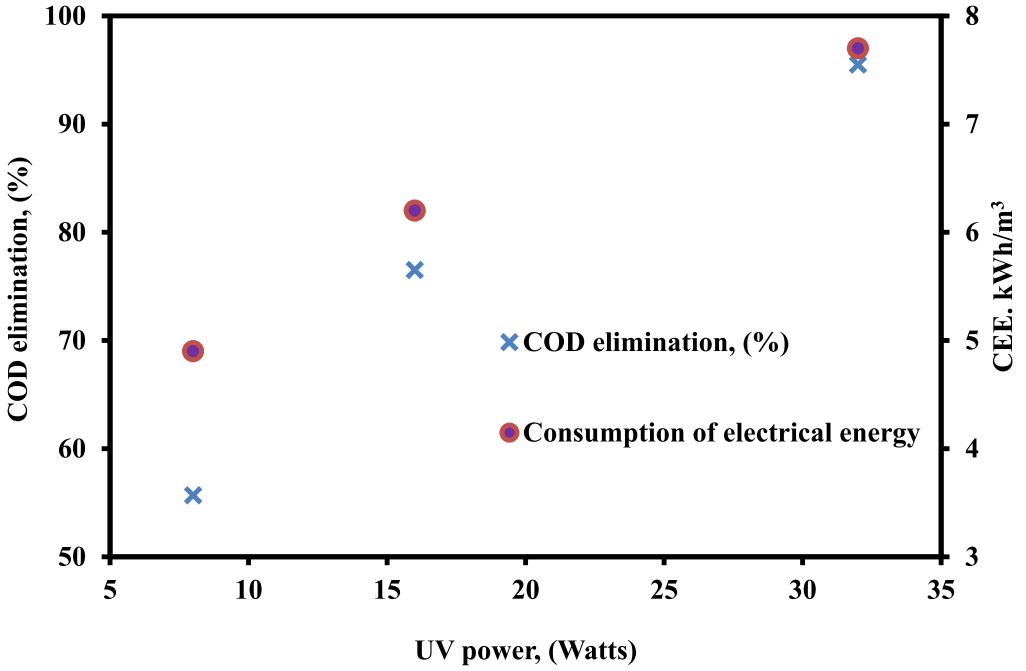


Figure 5. Influence of UV power on % COD elimination and CEE from wastewater by combined aerated/UV/EleC technique (Conditions of the experiment: TD = 75 min, AFR = 60 l min^{-1}, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP = Fe/Fe).

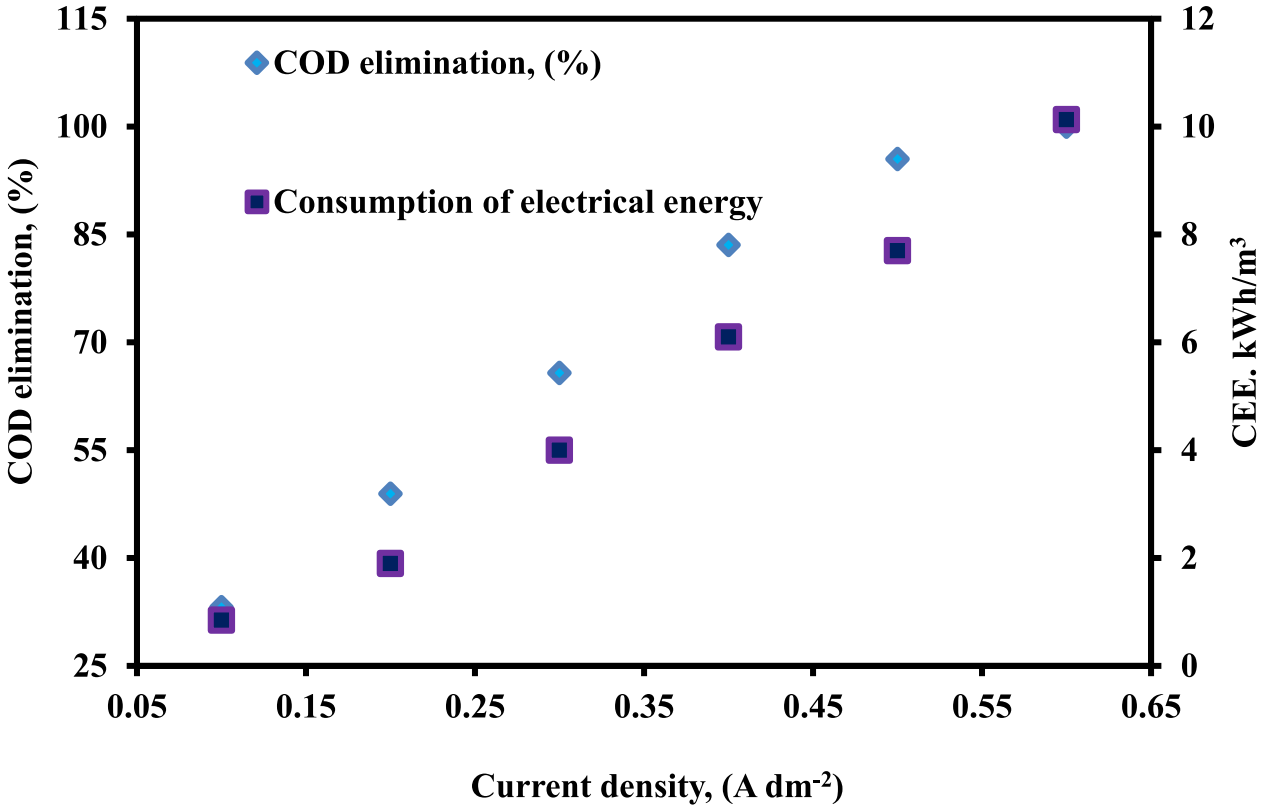


Figure 6. Influence of J on % COD elimination and CEE from wastewater by combined Aerated/UV/EleC method (Experimental conditions: TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, COD = 2500 mg l^{-1}, pH = 7, GBE = 1 cm, and EleP = Fe/Fe).

0.6 A dm^{-2}. This might be due to the fact that the voltage of the cell is directly connected to the J.[74] In subsequent experiments, a J of 0.5 A dm^{-2} was employed to balance the efficiency of COD removal with CEE.

Impact of COD.—With a J of 0.5 A dm^{-2}, the experiment used a range of initial COD values, from 1250 to 6250 mgl^{-1}. The reduction of COD declined from 100 to 42.75%, whereas CEE diminished from 8.50 to 4.3 kWhr m^{-3}, respectively, when, as seen

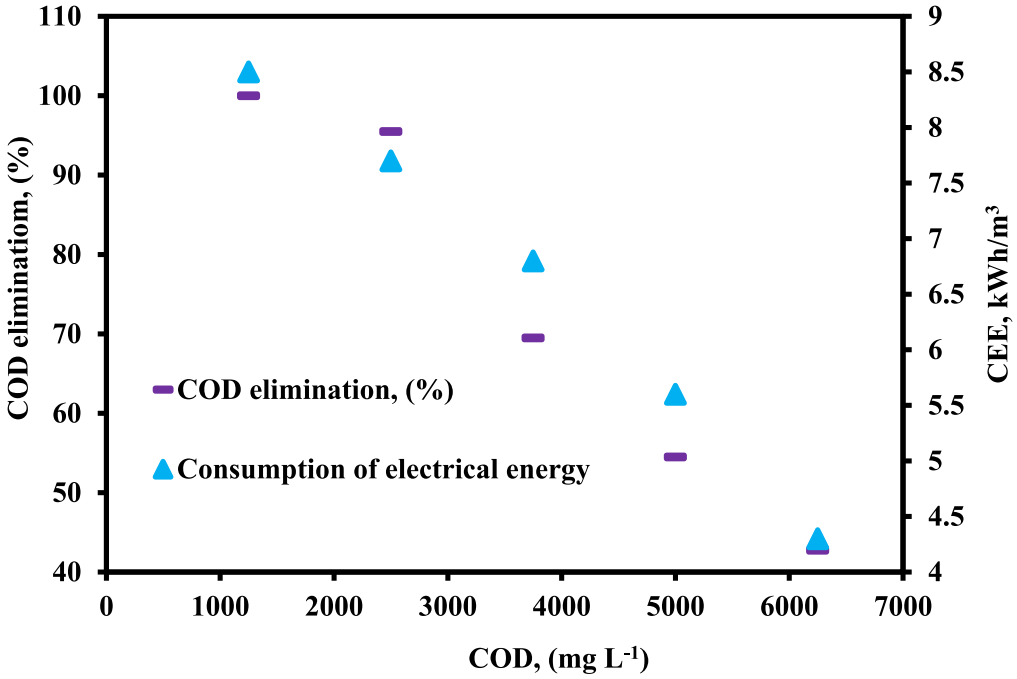


Figure 7. Impact of COD on % COD elimination and CEE from wastewater by combined aerated/UV/EleC technique (Conditions of the experiment: TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, pH = 7, GBE = 1 cm, and EleP = Fe/Fe).

in Fig. 7, during a 75 min treatment period, the initial CODs were increased from 1250 to 6250 mgl^{-1}. It was determined that the quantity of COD that was eliminated was 1000 and 3600 mgl^{-1}, respectively, for the starting concentration of 1000 and 6250 mg l^{-1}. The removal of COD has decreased as the initial concentration of solutions has increased, while the quantities of pollutant concentration eliminated have increased. Faraday's law states that a fixed volume of Fe^{2+} passes to the solution to raise the initial effluent concentration at a constant galvanostatic value of J and duration. Under same J and TD, the release rate of ·OH radicals and the number of flocs produced with $Fe(OH)_3$ remained nearly constant.[31,75] The primary mechanism for pollutant elimination in the hybrid aerated+UV+EleC process was ion adsorption onto iron hydroxide flocs; however, the adsorption capacity of the flocs was constrained. The fact that the initial COD content was higher suggests that the wastewater solution contained a greater quantity of pollutants from the beginning. As a result, the hydroxide matrices possess an enhanced ability to collect and remove the increased COD from the solution by sweep coagulation. On the other hand, as the initial COD content of the wastewater rises, the electrical energy consumption decreases due to the higher amount of COD eliminated at constant J.

Influence of pH.—One of the key factors influencing the hybrid EleC process effectiveness is the pH of the solution, which primarily influences the speciation of contaminants and coagulating agents.[76,77] Figure 8 displays the rates of COD removal as well as the values of the solution pH changes. Figure illustrates how pH affects the % of COD elimination efficiencies and CEE. When the pH of the solution is increased from 2 to 7, the COD elimination efficiency first rises from 29.50% to an ideal value of 95.50%. Similarly, the amount of CEE that is consumed rises from 5.84 to 7.70 kWhr m^{-3}. The maximum COD elimination efficiency (95.50%) and CEE (7.70 kWhr m^{-3}) were attained at an optimum pH of the solution 7. The findings indicated that the optimal pH for COD removal was 7, aligning with previous studies; the EleC process with iron anodes exhibited superior performance in neutral and mildly alkaline environments. When the pH of the solution was low, the soluble Fe^{2+} and Fe^{3+} were the predominant forms. At the same time, less insoluble $Fe(OH)_{3(S)}/FeOOH_{(S)}$ coagulants were formed under acidic circumstances due to a slower rate of Fe^{2+} oxidation to Fe^{3+} than in neutral and alkaline settings,[77,78] which therefore reduced the removal of COD. Furthermore, by constantly consuming OH^-, additional iron hydroxide complexes such as $Fe(OH)_4$ and $Fe(OH)_6$ were produced at pH values higher than 7.[77,78] However, due to their poor coagulation capability, these ions are not useful for the treatment. The efficacy of COD removal would also be decreased at high pH ranges due to lower anode dissolution and oxidation of the anode hydroxide ions. It was for this reason that all following experiments were carried out under the circumstance of a pH that was neutral.

Impact of GBE.—In a hybrid EleC process, the gap between electrodes (GBE) is a crucial operational parameter for attaining complete pollutant removal while reducing operating costs.[28,38] The impact of GBE on the aerated+UV+EleC process was examined utilizing measurements from 1 to 5 cm under specified operating conditions: TD = 75 min, pH = 7, AFR = 60 l min^{-1}, UV power = 32 W, COD = 2500 mg l^{-1}, J = 0.50 A dm^{-2}, and EleP= Fe/Fe. Figure 9 illustrates that augmenting the GBE from 1 to 5 cm decreased the % COD elimination efficiency from 95.50% to 30% and elevated the CEE from 7.70 to 25.8 kWh m^{-3}. As GBE increases, Fe^{2+} at the anode decreases as a result of anodic oxidation being inhibited by Ohmic losses linked to anode and cathode overvoltage and mass transfer resistance.[79] Consequently, both the adsorption of contaminants at a higher GBE and the formation of coagulants in the middle will be slowed down.[79] Conversely, when the GBE is kept to a minimum, the electrolytic process is facilitated by the decreased resistance of current flow in solution, which raises the percentage of COD elimination. As a result, the best inter–electrode spacing is chosen to be 1 cm in order to reduce the presence of CEE while simultaneously increasing the efficacy of COD removal.

Effect of EleP.—As shown in Fig. 10a, the COD removal efficacy of various electrode combinations is shown at the same J = 0.50 A dm^{-2} and an initial pH of 7. The maximum COD elimination efficiency was achieved by combining the Fe anode and Fe cathode, achieving 95.50% after 75 min of treatment, however, Al/Fe, Al/Al, and Fe/Al combinations demonstrated efficiencies of 68%, 78%, and

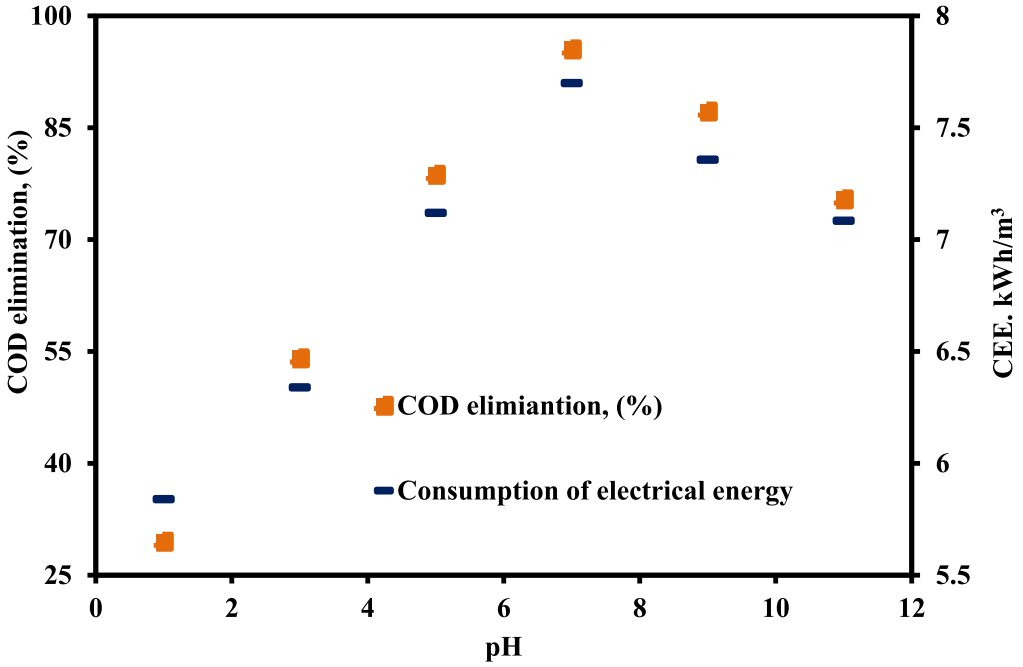


Figure 8. Influence of pH on % COD elimination and CEE by combined aerated/UV/ EleC method (Conditions of the experiment: TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, GBE = 1 cm, and EleP = Fe/Fe).

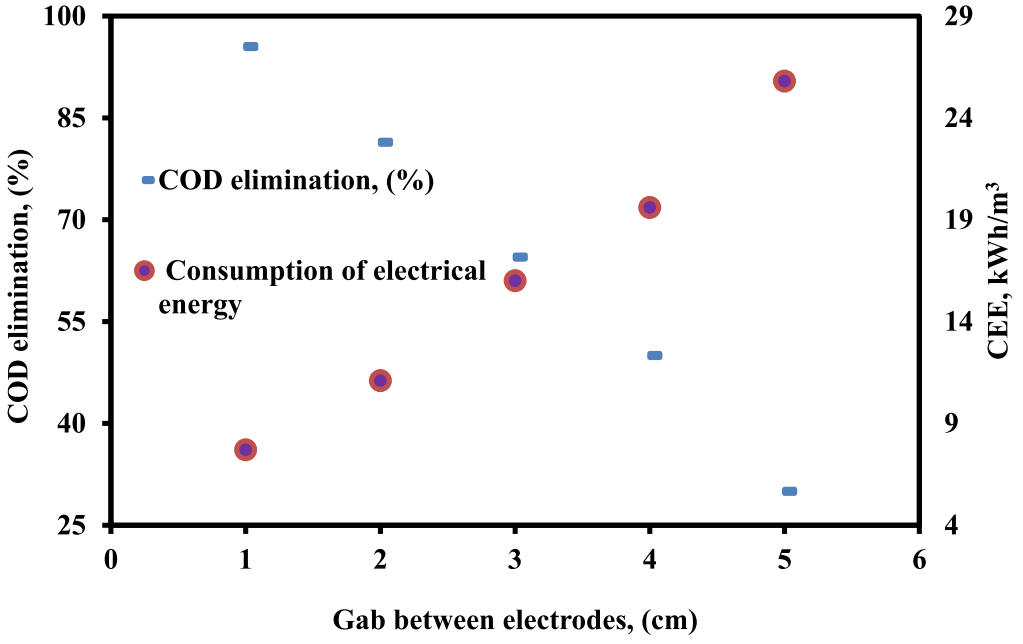


Figure 9. Impact of GBE on % COD elimination and CEE from wastewater by combined aerated/UV/EleC method (Conditions of the experiment: TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, and EleP = Fe/Fe).

80.60%, respectively. Figure 10b illustrates the difference in the amount of electrical energy that was used by the various combinations of electrodes. The highest specific energy consumption recorded was 7.7 kWh m^{-3} using a Fe/Fe combination after 75 min of treatment. The Fe has lower conductivity than *Al*, necessitating a greater voltage at equivalent current density, resulting in Fe electrode combinations using more energy than Al electrodes.

According to Faraday's rule, the amount of dissolved coagulant metal is directly proportional to the molar mass of the metal and inversely proportional to the number of electrons lost. On the other hand, the amount of electrons that *Fe* loses during the reaction is significantly lower, and its molar mass is twice as high as that of *Al*.[38,80] Consequently, Fe electrodes generated a greater quantity of coagulant to capture contaminants and also yielded increased sludge production. The development of a dense Al_2O_3 layer throughout the procedure restricted the dissolution of the *Al* anode combinations, leading to decreased removal efficiency. It was also noted that denser bubbles developed on the surface of the *Al* cathode due to the combination of the *Fe* anode and *Al* cathode. Smaller bubbles are believed to enhance the aggregation of metal flocs and contaminants, hence increasing removal efficiency. Therefore, *Fe/Fe* was thought to be the best combination for additional research when power consumption and COD removal efficiency were balanced.

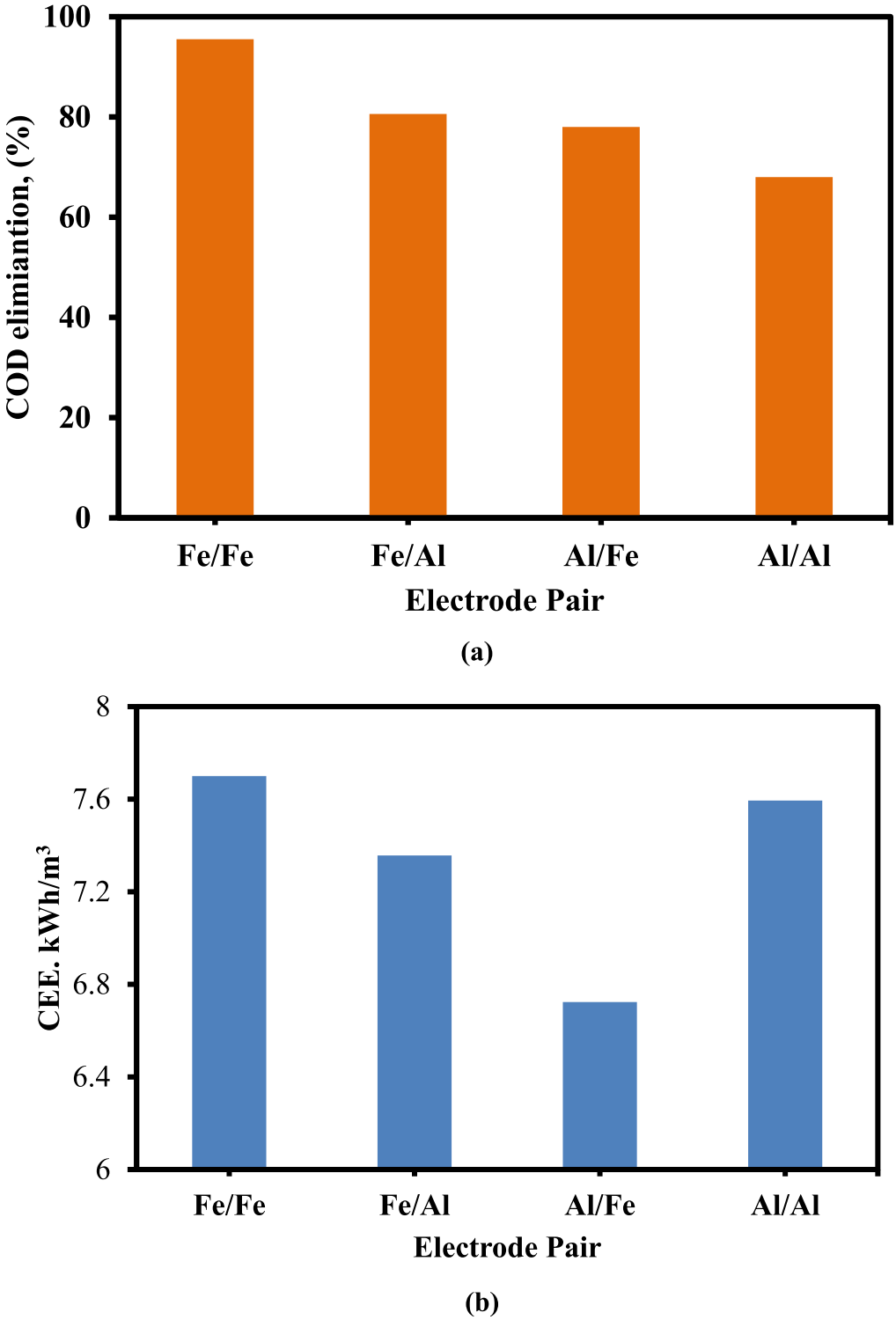


Figure 10. Influence of EleP on % COD elimination and CEE from wastewater by combined aerated/UV/EleC process (Conditions of the experiment: TD = 75 min, AFR = 60 l min^{-1}, UV power = 32 W, J = 0.50 A dm^{-2}, COD = 2500 mg l^{-1}, pH = 7, and GBE = 1 cm).

Instrumental analysis.—Fig. 11 is an illustration of the UV/Vis–Spectra that were developed for the evaluation of LLW. After the application of each step, a comparison was done with the initial LLW, which was as: aeration, UV treatment, EleC, as well as the combinations of aeration+UV, aeration+EleC, UV+EleC, and aeration+UV+EleC. Figure 11 indicates that the UV/Vis–spectra data demonstrate the superior efficiency of the aerated+UV+EleC process in decolorizing and degrading landfill leachate wastewater compared to alternative methods, including UV+EleC, aerated +EleC, EleC alone, aerated+UV, aerated alone, and UV alone.

Synergy index (SI).—It is vital to take into consideration the synergistic index (SI), which is often referred to as the enhancement factor, while establishing an integrated method for the treatment of wastewater.[81] The effect of a combination of two or more processes or variables is greater than the total of the effects of each of those

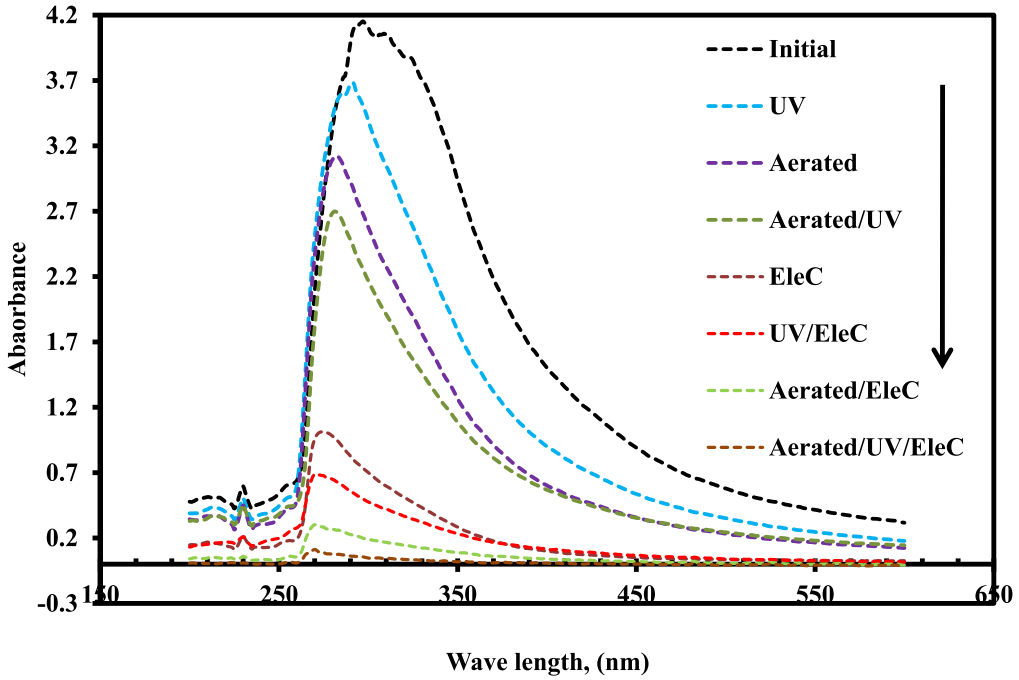


Figure 11. UV/Vis spectrophotometer analysis.

processes or variables taken separately. This concept is referred to as the SI. Equation 13 can be employed to calculate the SI by comparing the pollutant removal efficiency of the integrated process to the sum of the pollutant removal rates of the individual processes.

$$SI = \left(\frac{k_{Aerated/UV/EleC}}{k_{Aeraed} + k_{UV/EleC}} - 1 \right) * 100 \quad [13]$$

Where, $k_{Aerated/UV/EleC}$, $k_{Aerated}$, and $k_{UV/EleC}$ are the rate constants of the hybrid aerated/UV/EleC process, the individual aerated, and UV/EleC process, respectively. The aerated, UV, and EleC procedures' color and COD removal rates revealed a first-order process that was directly proportional to the solution's COD level. The rate constant (k) was determined using the firts-order equation based on the COD removal rate for each process, and it was discovered that for the process of aerated/UV/EleC of 1.625 min^{-1}, UV/EleC of 1.30 min^{-1}, and aerated of 0.20 min^{-1}, respectively. An enhancement factor of 8.50 was calculated based on the rate constant, and it was discovered that the synergistic impact of aerated and UV+EleC was SE $>$ 1. When the SI value fits within the positive range, it indicates that there is a positive synergistic influence. This is a sign that the impact is good. This integrated process is more efficient than the individual processes because of the following factors: (i) because there is no passive layer present on the surface of the electrode; (ii) enhanced capacity for mass transfer and activation of electrodes; and (iii) increased amounts of $^{\cdot}OH$ being released into the surroundings.[82–83]

Conclusions

Within the scope of this study, the treatment of wastewater derived from landfill leachate was explored by employing a variety of individual procedures as well as a combination of advanced oxidation and electrochemical techniques, including aeration alone, UV alone, EleC alone, and combinations of aeration/UV, UV/EleC, aeration/EleC, and aeration/UV/EleC processes, focusing on the % elimination of color and COD while considering electrical energy consumption. Taking into consideration the results of the experiments, it is possible to draw the conclusion that particular processes, such as aerated, UV, and EleC, perform less well when it comes to the treatment of wastewater derived from landfill leachate. However, the efficiency of the hybrid model of aerated, UV, and an EleC process is superior than that of the separate processes when they are applied. In comparison to the other processes, the combined aerated/UV/EleC process demonstrates a high level of color removal (100%) and COD removal (95.50%) while using 7.7 kWhr m^{-3} of electrical energy usage. This is the conclusion that can be drawn from our data. As a result of these discoveries, an alternative to the conventional physicochemical techniques for the treatment of wastewater is the combination of aerated and UV light with an electrocoagulation technique.

Acknowledgments

The authors acknowledge the financial support through the Researchers Supporting Project number (RSPD2025R768), King Saud University, Riyadh, Saudi Arabia.

ORCID

Perumal Asaithambi https://orcid.org/0000-0002-0533-0178

References

1. S. F. Ramli and H. Abdul Aziz, *Appl. Mech. Mater.*, **773–774**, 1163 (2015).
2. K. Faheem, S. U. Khan, M. Washeem, and S. U. Khan, *Int. J. Environ. Sci. Technol.*, **19**, 3625 (2022).
3. M. Dolatabadi, T. Świergosz, and S. Ahmadzadeh, *Sci. Total Environ.*, **772**, 145323 (2021).
4. X. Hu, X. Wang, Y. Ban, and B. Ren, *Environ. Technol.*, **32**, 945 (2011).
5. C. Wu, W. Chen, Z. Gu, and Q. Li, *Sci. Total Environ.*, **762**, 143131 (2021).
6. Z. Huang et al., *Sci. Total Environ.*, **790**, 148269 (2021).
7. S. Khoramipour, J. Mehralipour, and M. Hosseini, *Int. J. Environ. Anal. Chem.*, **103**, 7587 (2023).
8. S. Y. Cheng et al., *Chemosphere*, **262**, 127829 (2021).
9. S. S. Abu Amr and H. A. Aziz, *Waste Manag.*, **32**, 1693 (2012).
10. C. Ricordel and H. Djelal, *J. Environ. Chem. Eng.*, **2**, 1551 (2014).
11. M. A. A. Hamid, H. A. Aziz, and M. S. Yusoff, *Sustainable Solutions for Environmental Pollution*, **1**, 257 (2021).
12. P. Rafiee, M. Hosseini, and S. Ebrahimi, *React. Kinet. Mech. Catal.*, **131**, 319 (2020).
13. C. Jegadeesan, A. Somanathan, R. B. Jeyakumar, and V. Godvin Sharmila, *Environ. Technol.*, **44**, 4441 (2023).
14. J. Sun, X. Li, J. Feng, and X. Tian, *Water Res.*, **43**, 4363 (2009).
15. F. Ghanbari, J. Wu, M. Khatebasreh, D. Ding, and K. Y. A. Lin, *Sep. Purif. Technol.*, **242**, 116828 (2020).
16. J. Torkashvand et al., *Environ. Sci. Pollut. Res.*, **28**, 47741 (2021).

17. D. Ankoliya, A. Mudgal, M. K. Sinha, V. Patel, and J. Patel, *Mater. Today Proc.*, **77**, 117 (2023).
18. S. Boinpally, A. Kolla, J. Kainthola, R. Kodali, and J. Vemuri, *Water Cycle*, **4**, 26 (2023).
19. P. B. Bhagawati et al., *Advanced Oxidation Processes in Dye-Containing Wastewater*, ed. S. S. Muthu and A. Khadir (Springer Nature, Singapore, Singapore) 305 (2022).
20. J. Abdollahi, M. R. Alavi Moghaddam, and S. Habibzadeh, *Chemosphere*, **312**, 137212 (2022).
21. J. Akansha, P. V. Nidheesh, A. Gopinath, K. V. Anupama, and M. S. Kumar, *Chemosphere*, **253**, 126652 (2020).
22. P. V. Nidheesh and Ö. Gökkuş, *Sep. Sci. Technol.*, **58**, 2041 (2023).
23. Ö. Gökkuş, E. Brillas, and I. Sirés, *Sci. Total Environ.*, **912**, 169143 (2024).
24. Z. Al-Qodah, M. Tawalbeh, M. Al-Shannag, Z. Al-Anber, and K. Bani-Melhem, *Sci. Total Environ.*, **744**, 140806 (2020).
25. M. Alimohammadi, A. Mesdaghinia, M. H. Shayesteh, H. J. Mansoorian, and N. Khanjani, *Int. J. Environ. Sci. Technol.*, **16**, 8239 (2019).
26. M. Payami Shabestar, M. R. Alavi Moghaddam, and E. Karamati-Niaragh, *Environ. Sci. Pollut. Res.*, **28**, 67214 (2021).
27. V. K. Sandhwar and B. Prasad, *Korean J. Chem. Eng.*, **35**, 909 (2018).
28. Z. Al-Qodah, Y. Al-Qudah, and E. Assirey, *Sep. Sci. Technol.*, **55**, 2334 (2020).
29. P. P. Das et al., *Chemosphere*, **263**, 128370 (2021).
30. Z. Q. He et al., *Environ. Technol.*, **28**, 1257 (2007).
31. M. Mehralian, M. Khashij, and A. Dalvand, *Environ. Sci. Pollut. Res.*, **28**, 45041 (2021).
32. Z. Al-Qodah and M. Al-Shannag, *Sep. Purif. Rev.*, **48**, 143 (2019).
33. P. Asaithambi, B. Sajjadi, A. R. Abdul Aziz, and W. M. A. B. W. Daud, *Process Saf. Environ. Prot.*, **104**, 406 (2016).
34. S. Farhadi, B. Aminzadeh, A. Torabian, V. Khatibikamal, and M. A. Fard, *J. Hazard. Mater.*, **219–220**, 35 (2012).
35. M. Moradi and G. Moussavi, *Chem. Eng. J.*, **358**, 1038 (2019).
36. T. Emerick, J. L. Vieira, M. H. L. Silveira, and J. J. João, *J. Environ. Chem. Eng.*, **8**, 104308 (2020).
37. M. Moradi, Y. Vasseghian, H. Arabzade, and A. M. Khaneghah, *Chemosphere*, **263**, 128314 (2021).
38. T. Tavangar, K. Jalali, M. A. Alaei Shahmirzadi, and M. Karimi, *Sep. Purif. Technol.*, **216**, 115 (2019).
39. O. Ucevli and Y. Kaya, *J. Environ. Chem. Eng.*, **9**, 104946 (2021).
40. Z. B. Gönder, G. Balcıoğlu, I. Vergili, and Y. Kaya, *Chemosphere*, **253**, 126713 (2020).
41. N. Karimi, S. A. Mirbagheri, R. Nouri, and A. Bazargan, *Results Eng*, **17**, 100770 (2023).
42. O. Khalifa, F. Banat, C. Srinivasakannan, J. Radjenovic, and S. W. Hasan, *J. Water Process Eng.*, **36**, 101290 (2020).
43. S. Jallouli et al., *J. Water Process Eng.*, **38**, 101642 (2020).
44. S. Cotillas et al., *Electrochim. Acta*, **140**, 396 (2014).
45. A. Kumar, P. V. Nidheesh, and M. Suresh Kumar, *Chemosphere*, **205**, 587 (2018).
46. M. Priya and J. Jeyanthi, *Microchem. J.*, **150**, 104070 (2019).
47. E. Science,.N K Anuar, N S M Zin, L W Zailani, S N A Salleh, and N A Akbar et al., *IOP Conf. Ser.: Earth Environ. Sci.*, **1022**, 012067 (2022).
48. A. Syakdani, Y. Bow, T. Dewi, A. Ja, and S. Arita, *Journal on Advanced Science, Engineering and Information Technology*, **10**, 400 (2020).
49. P. R. F. da Costa, E. C. T. de, A. Costa, S. S. L. Castro, A. S. Fajardo, and C. A. Martínez-Huitle, *J. Electroanal. Chem.*, **834**, 79 (2019).
50. P. Valero et al., *J. Environ. Manage.*, **198**, 256 (2017).
51. E. Mousset et al., *Water Res.*, **200**, 117234 (2021).
52. E. GilPavas, I. Dobrosz-Gómez, and M. Á. Gómez-García, *J. Water Process Eng.*, **24**, 49 (2018).
53. J. Anotai, S. Singhadech, C.-C. Su, and M.-C. Lu, *J. Hazard. Mater.*, **196**, 395 (2011).
54. S. Irmak, H. I. Yavuz, and O. Erbatur, *Appl. Catal. B Environ.*, **63**, 243 (2006).
55. F. C. Moreira, S. Garcia-Segura, V. J. P. Vilar, R. A. R. Boaventura, and E. Brillas, *Appl. Catal. B Environ.*, **142–143**, 877 (2013).
56. S. Campos et al., *Process Saf. Environ. Prot.*, **169**, 660 (2023).
57. P. Asaithambi, R. Govindarajan, M. B. Yesuf, and E. Alemayehu, *Sep. Purif. Technol.*, **233**, 115935 (2020).
58. F. E. Titchou et al., *Environ. Res.*, **204**, 112353 (2022).
59. S. Singh, S. L. Lo, V. C. Srivastava, Q. Qiao, and P. Sharma, *J. Taiwan Inst. Chem. Eng.*, **118**, 169 (2021).
60. S. Simon, B. K. Suresh, and T. S. Anantha-Singh, *Chemosphere*, **339**, 139692 (2023).
61. A. Shahedi, A. Jamshidi-Zanjani, A. K. Darban, M. Homaee, and F. Taghipour, *J. Hazard. Mater. Adv.*, **17**, 100550 (2025).
62. P. Asaithambi et al., *J. Environ. Manage.*, **320**, 115926 (2022).
63. A. Shahedi, A. K. Darban, A. Jamshidi-Zanjani, F. Taghipour, and M. Homaee, *Water (Switzerland)*, **15**, 581 (2023).
64. S. Kumari and R. N. Kumar, *Chemosphere*, **305**, 135476 (2022).
65. P. M. Lakshmi and P. Sivashanmugam, *Sep. Purif. Technol.*, **116**, 378 (2013).
66. F. H. Borba et al., *J. Water Process Eng.*, **23**, 207 (2018).
67. M. A. García-Morales, G. Roa-Morales, C. Barrera-Díaz, B. Bilyeu, and M. A. Rodrigo, *Electrochem. Commun.*, **27**, 34 (2013).
68. P. V. Nidheesh and T. S. A. Singh, *Chemosphere*, **181**, 418 (2017).
69. M. Keramati and B. Ayati, *Process Saf. Environ. Prot.*, **126**, 356 (2019).
70. A. R. A. Aziz, P. Asaithambi, and W. M. A. B. W. Daud, *Process Saf. Environ. Prot.*, **99**, 227 (2016).
71. A. A. Márquez, O. Coreño, and J. L. Nava, *Process Saf. Environ. Prot.*, **169**, 579 (2023).
72. I. Sanni, M. R. Karimi Estahbanati, A. Carabin, and P. Drogui, *Sep. Purif. Technol.*, **282**, 119992 (2022).
73. N. Dizge et al., *J. Water Process Eng.*, **21**, 52 (2018).
74. R. Ahlawat, V. C. Srivastava, I. D. Mall, and S. Sinha, *CLEAN—Soil, Air, Water*, **36**, 863 (2008).
75. B. Merzouk et al., *Chem. Eng. J.*, **149**, 207 (2009).
76. J. M. Zaldivar-Díaz et al., *J. Water Process Eng.*, **51**, 103369 (2023).
77. S. K. Patel, S. C. Shukla, and A. K. Prajapati, *Chem. Eng. Process. - Process Intensif.*, **188**, 109360 (2023).
78. A. Dalvand, M. Gholami, A. Joneidi, and N. M. Mahmoodi, *Clean - Soil, Air, Water*, **39**, 665 (2011).
79. C. A. Igwegbe, O. D. Onukwuli, J. O. Ighalo, and C. J. Umembamalu, *Chem. Eng. J. Adv.*, **6**, 100107 (2021).
80. F. Ghanbari et al., *Sep. Purif. Technol.*, **266**, 118533 (2021).
81. A. Dargahi et al., *Biomass Convers. Biorefinery*, **13**, 10615 (2021).
82. S. Şahinkaya, *J. Ind. Eng. Chem.*, **19**, 601 (2013).
83. M. Amarzadeh et al., *J. Environ. Manage.*, **324**, 116333 (2022).