

Received: 25 December 2023

Revised: 3 February 2024

Accepted: 6 February 2024

# Optimization of operational parameters using central composite design in the peroxi-alternating current-electrocoagulation process for the pollutant removal with determination of power consumption from industrial wastewater

Perumal Asaithambi | Wendesen Mekonin Desta | Mohammed Hussien |  
Mamuye Busier Yesuf | Dejene Beyene

Faculty of Civil and Environmental  
Engineering, Jimma Institute of  
Technology, Jimma University, Jimma,  
Ethiopia

## Correspondence

Perumal Asaithambi and Dejene Beyene,  
Faculty of Civil and Environmental  
Engineering, Jimma Institute of  
Technology, Jimma University, Jimma, PO  
Box - 378, Ethiopia.  
Email: [asaithambi.perumal@ju.edu.et](mailto:asaithambi.perumal@ju.edu.et);  
[drasaithambi2014@gmail.com](mailto:drasaithambi2014@gmail.com) and  
[dejene.beyene@ju.edu.et](mailto:dejene.beyene@ju.edu.et).

## Funding information

Jimma University

## Abstract

The utilization of electrochemical and advanced oxidation technologies for industrial wastewater (IW) treatment has grown in popularity during the last two decades. The effectiveness of several methods for treating IW, including hydrogen peroxide ( $H_2O_2$ ), direct-current (DC) and alternating-current (AC)-electrocoagulation (EC), and the combination of  $H_2O_2$  with DC/AC-EC ( $H_2O_2$ -DC/AC-EC) processes were all investigated. In comparison to the  $H_2O_2$ , DC/AC-EC, and  $H_2O_2$ -DC/AC-EC technologies, the results showed that the  $H_2O_2$ -AC-EC process produced 100% total colour and 100% chemical oxygen demand (COD) removal efficiency with a low power consumption of 4.4 kWhm<sup>-3</sup>. The  $H_2O_2$ /AC-EC technology was optimized for treating IW using a response surface methodology approach based on a central composite design using a five-factor level. Utilizing statistical and mathematical techniques, the optimum parameters were determined to minimize consumption of power (1.02 kWhm<sup>-3</sup>) and maximum COD elimination (75%). The experimental parameters comprised the following:  $H_2O_2$  of 600 mg/L, current of 0.65 Amp, pH of 7.6, COD of 1600 mg/L, and treatment time (TT) of 1.26 h. When using a Fe/Fe electrode combination with the wastewater pH of 7, the COD removal efficiency was shown to be enhanced by increasing the TT, current and  $H_2O_2$ , and decreasing the COD concentration. The synergistic impact, quantified as the combined efficiency of eliminating % COD utilizing the  $H_2O_2$ , AC-EC, and  $H_2O_2$ /AC-EC

**Abbreviations:** AC, Alternating-Current; ANOVA, Analysis of Variance; AR, Analytical Reagent; BOD, Biochemical Oxygen Demand; CCD, Central Composite Design; CEC, Continuous Electrocoagulation; COD, Chemical Oxygen Demand; DC, Direct-Current; EC, Electrocoagulation;  $H_2O_2$ , Hydrogen Peroxide; IW, Industrial Wastewater; PC, Peroxi-Coagulation; PEC, Peroxi-Electrocoagulation; RSM, Response Surface Methodology; SE, Synergistic Effect; TDS, Total Dissolved Solids; TSS, Total Suspended Solids; TT, Treatment Time.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2024 The Authors. *Electrochemical Science Advances* published by Wiley-VCH GmbH.

procedures, was found to be 15.75%. Therefore, employing a hybrid H<sub>2</sub>O<sub>2</sub>-AC-EC approach is considerably more effective in treating IW.

#### KEYWORDS

colour and COD removal, consumption of power, DC/AC-EC, H<sub>2</sub>O<sub>2</sub>, industrial wastewater, synergistic index

## 1 | INTRODUCTION

Much emphasis has been paid to the electrocoagulation (EC) technique for treating wastewater from a variety of industries, including oily wastewater,<sup>[1,2]</sup> baker's yeast,<sup>[3]</sup> metal-plating,<sup>[4]</sup> coloured textile,<sup>[5]</sup> dairy,<sup>[6]</sup> shipyard,<sup>[7]</sup> reactive blue 19 synthetics,<sup>[8]</sup> slaughterhouse,<sup>[9]</sup> domestic,<sup>[10]</sup> pulp and paper,<sup>[11]</sup> landfill leachate,<sup>[12]</sup> municipal,<sup>[13]</sup> brewery,<sup>[14]</sup> dye bath,<sup>[15]</sup> marble processing,<sup>[16]</sup> etc. When compared to other conventional methods, the EC process offers several advantages, including easy experimental setup and operation, shorter treatment times (TTs), no chemical additions, quicker floc sedimentation and less sludge development, and high pollution removal efficiency with less electricity consumption.<sup>[17,18]</sup> EC is a process that involves the release of metal ions (Fe<sup>2+</sup> or Fe<sup>3+</sup>, Al<sup>3+</sup>) by anodic oxidation. Sacrificial soluble iron (Fe) and/or aluminium (Al) are used as anodes and/or cathodes to accomplish this.<sup>[19,20]</sup> Subsequently, these ions react with hydroxyl ions released from the cathode, resulting in the production of iron or aluminium hydroxides and promoting the aggregation of particles into flocs.<sup>[21]</sup>

The application of direct current (DC) is prevalent in the electrochemical process for the treatment of many types of wastewater.<sup>[22,23]</sup> The main constraints of the DC-EC technology are the unavoidable formation of an impermeable oxide layer on the cathode and the presence of corrosion on the anode caused by oxidation. These factors hinder the efficient flow of electrical current between the anode and cathode. As a result, the DC-EC method was disregarded since its outcomes showed poorer pollutant removal effectiveness together with high energy and operational expenses.<sup>[24]</sup> To reduce the disadvantage of the DC-EC process with cathode passivation, either the anode or cathode may be replaced on a regular basis in DC mode operation, or the alternating-current-EC (AC-EC) method may be utilized.<sup>[25]</sup>

Research by Alimohammadi et al.,<sup>[26]</sup> revealed that, as compared to the DC method, the AC and polarity inverter EC approach was much more successful in removing fluoride from drinking water. Bian et al.,<sup>[27]</sup> used both DC and AC-powered electrochemical methods to demonstrate

the efficacy of the high salinity bilge water treatment approach. Continuous AC was shown to be more effective than DC mode utilization in maintaining the same output at lower energy costs.

Arabameri et al.,<sup>[28]</sup> examined the DC versus AC modes of the EC system for the removal of Ni<sup>2+</sup> from aqueous solution. They found that the average amount of remaining nickel in both the DC and AC modes was 44.06 and 43.91 mg/L, the energy consumption was 34.9 and 29.2 kWh/kg Ni removed, and the electrode consumption was 2.3 and 1.2 kg Al/kg Ni removed, respectively. Furthermore, they determined that the shift from traditional DC to AC coagulation resulted in a significant decrease of over 16% in energy usage and a substantial reduction of 47% in electrode consumption. Karamati-Niaragh et al.,<sup>[29]</sup> employed a continuous EC (CEC) technique to study the effects of AC and DC on nitrate removal and operating costs. The author discovered that the AC mode nitrate removal was marginally more effective than the DC mode. Furthermore, they found that switching from DC to AC lowered operational expenses by almost 40% on average.

The peroxi-AC-EC and AC-EC methods were developed by Zhang et al.<sup>[30]</sup> to improve the rate of chemical oxygen demand (COD) removal while lowering the electrode loss and power consumption of the indigo dye solution. According to their findings, the COD elimination rates by the AC-EC and peroxi-AC-EC processes were 51.19% and 78.09%, respectively. Additionally, they discovered that the coupled system used for the investigation of the specific energy consumption of COD elimination used less energy than the DC EC process. Sandhwar and Prasad,<sup>[31]</sup> concentrated on a comparative analysis of the peroxi-coagulation (PC), peroxi-EC (PEC) and EC methods for treating aqueous solutions that included the main toxic components of wastewater. They achieved maximum COD removal of 60.76%, 73.91% and 66.68% with energy consumption (kWh/kg COD removed) of 95.81, 49.58 and 69.26 under optimal circumstances using the EC, PEC and PC processes. The author finally discovered that the PEC was the most effective treatment among the EC, PEC and PC methods due to its greatest elimination capacity and lowest energy usage.

Prior research has shown that the utilization of the AC electrochemical method has benefits in reducing pollutants in wastewater such as cadmium,<sup>[32]</sup> lead and zinc,<sup>[33]</sup> copper,<sup>[34]</sup> brewery wastewater,<sup>[24]</sup> distillery industrial effluent,<sup>[35]</sup> synthetic and real smelting wastewater,<sup>[36]</sup> aqueous solution,<sup>[37]</sup> etc. The benefits of using an AC electrochemical technique to reduce pollutants in synthetic wastewater have been shown in previously published research. Simultaneously, there have been a limited number of studies conducted using real industrial wastewater.<sup>[38]</sup> Electrical energy utilization is a crucial aspect of DC/AC-EC processes, not only because it helps remove toxins from industrial wastewater, in addition because of its practical and financial importance.

However, it is important to consider energy consumption as a crucial aspect of electrochemical technology, along with its ability to effectively remove pollutants. This is necessary in order to make a fair comparison between electrochemical processes and other conventional treatment methods. The utilization of the peroxi-DC/AC-EC method shows promise in eliminating pollutants from industrial wastewater while also accurately measuring power consumption. However, there is a lack of information on the application of this technique.

The objective of this study was to assess the efficacy of several methods in treating industrial wastewater (IW) by evaluating the removal efficiency of colour and COD, as well as the consumption of power associated with each approach ( $H_2O_2$ , DC/AC-EC and  $H_2O_2$ -DC/AC-EC). Furthermore, evaluate the possible synergistic effect (SE) by comparing the outcomes of the  $H_2O_2$ -AC-EC approach with those of the  $H_2O_2$  and AC-EC processes conducted independently. The operating parameters of the hybrid  $H_2O_2$ -AC-EC process were adjusted using a central composite design (CCD) approach. These parameters include  $H_2O_2$  concentration (A), current intensity (B), pH level (C), COD, concentration (D) and TT duration (E). The key objectives of optimizing the hybrid  $H_2O_2$ -AC-EC technology for the treatment of industrial wastewater (IW) are to maximize the efficiency of % COD removal and minimize the consumption of power.

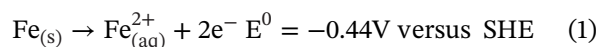
For the five variables that were selected, the combined impact of factors was examined using CCD statistical analysis utilizing Design-Expert Software 13.0.<sup>[39]</sup> It was applied to better understand and evaluate the ways in which specific operational parameters impacted the COD elimination efficiency and consumption of power. The design model variables and levels are shown in Table 1, where each independent variable has been coded at five different levels ranging from  $-2$  to  $+2$ .

## 1.1 | Theoretical background of EC and $H_2O_2$ -EC processes

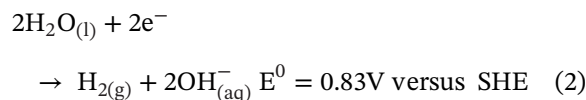
### 1.1.1 | EC process

The widely acknowledged method of eliminating contaminants by EC using iron electrodes can be expressed as.<sup>[19,20,40]</sup>

At the anode:



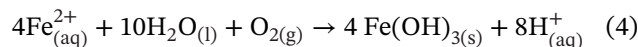
At the cathode:



Overall reaction:



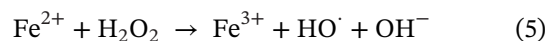
The presence of oxygen causes the dissolved  $Fe^{2+}$  to oxidize and become insoluble  $Fe(OH)_3$ .



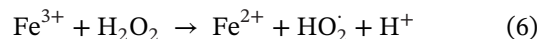
By complexation or electrostatic attraction followed by coagulation, the  $Fe(OH)_{n(s)}$  that remain in the aqueous stream as a gelatinous suspension can remove the contaminants from the wastewater.

### 1.1.2 | $H_2O_2$ -EC process

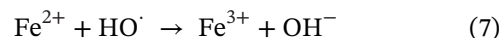
In an EC system,  $H_2O_2$  is introduced into the system, while a sacrificial iron (Fe) anode is utilized as the source of  $Fe^{2+}$ .<sup>[19,20]</sup>



The propagation of this reaction mostly occurs through the regeneration of ferrous ions, achieved by reducing the resulting ferric species using  $H_2O_2$ .



The rate of consumption of ferrous ions exceeds that of production. Furthermore, hydroxyl radicals have a rate constant of  $3.2-4.3 \times 10^8 \text{ M}^{-1}\text{s}^{-1}$ , which allows them to quickly degrade ferrous ions.<sup>[41]</sup>



**TABLE 1** Coded and actual values of the variables of the design of experiments for the peroxi-AC-EC process.

Factor	Name	Units	Type	Minimum	Maximum	Coded low	Coded high	Mean	Std. dev.
A	H <sub>2</sub> O <sub>2</sub>	mg/L	Numeric	120	600	-1 ↔ 240	+1 ↔ 480	360	108.42
B	Current	Amp	Numeric	0.14	0.70	-1 ↔ 0.28	+1 ↔ 0.56	0.42	0.1265
C	pH	-	Numeric	3	11	-1 ↔ 5.00	+1 ↔ 9	7	1.81
D	COD	mg/L	Numeric	1600	8000	-1 ↔ 3200	+1 ↔ 6400	4800	1445.61
E	TT	h	Numeric	1	3	-1 ↔ 1.50	+1 ↔ 2.50	2	0.4518

Therefore, to sustain the formation of hydroxyl radicals at a reasonable level, a higher dose of ferrous ions is required. The neutralization stage of the Fenton process produces a substantial volume of ferric hydroxide sludge, necessitating further separation and disposal procedures.

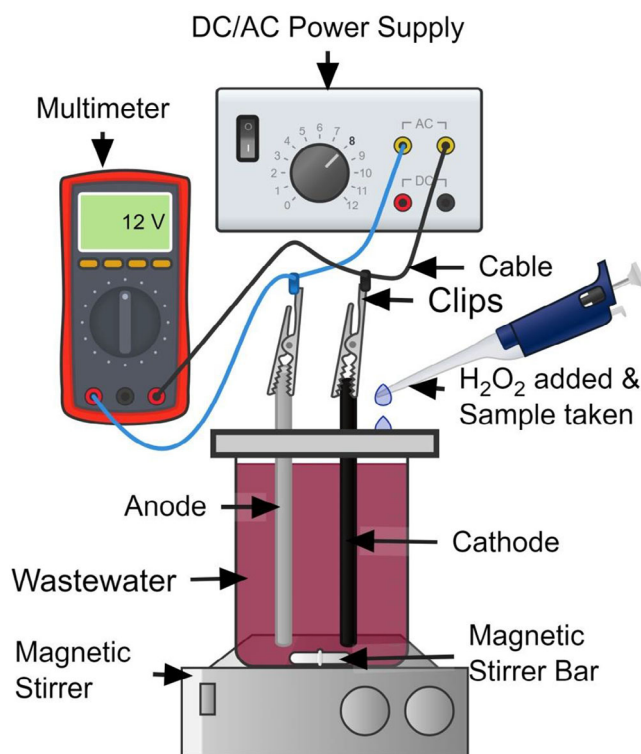
## 2 | MATERIAL AND METHODS

### 2.1 | Wastewater collection and analysis

The wastewater was obtained from the distillery industrial sector located in Addis Ababa, Ethiopia by the utilization of a grab sample method. The industrial wastewater from the distillery was subjected to analysis to determine its quality characteristics, including colour (dark brown), odour (burnt sugar), pH (4.2–4.4), COD (80,000–90,000 mg/L), BOD (7000–8000 mg/L), total suspended solids (TSS) (14.44 g/L) and total dissolved solids (TDS) (5450–5650 mg/L) in accordance with the conventional analysis approach.<sup>[42]</sup> In the studies, several chemicals were utilized, such as Ag<sub>2</sub>SO<sub>4</sub>, HgSO<sub>4</sub>, HCl, H<sub>2</sub>SO<sub>4</sub>, NaOH, K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> and (NH<sub>4</sub>)<sub>2</sub>Fe(SO<sub>4</sub>)<sub>2</sub>·6H<sub>2</sub>O, etc. All chemicals were obtained from Merck, and the analytical reagent grade was utilized exactly as received.

### 2.2 | Experimental configuration

The process configuration of H<sub>2</sub>O<sub>2</sub>-DC/AC-EC utilized to treat industrial wastewater is depicted in Figure 1. The batch construction of the electrochemical reactor comprises an acrylic sheet with a capacity of 2.25 L and an active working volume of wastewater of 2.0 L. The required COD content of wastewater was obtained by dilution of raw industrial effluent with distilled water. Before commencing the experiments, the original pH of the effluent was determined using a pH meter (Elico: Model LI120) and adjusted with 0.1 N H<sub>2</sub>SO<sub>4</sub> and 0.1 N NaOH solution to the desired level in the range of 3–11. As anode and/or cathode, an iron (Fe: grade MS 104) plate with dimensions of 12 × 15 × 0.1 cm was employed. A 12 × 11.50 × 0.1 cm was the effective electrode surface area. To allow for adequate


**FIGURE 1** Experimental setup of peroxi-AC-EC process.

stirring, the electrode bottom and the bottom of the electrochemical cell reactor were kept 2 cm apart. The electrode spacing between the anode and cathode was 1 cm. Before beginning each experiment, 15% HCl and distilled water were used to wash the electrodes. The galvanostatic operation was used to regulate the current when the anode and cathode were connected in monopolar parallel to a DC/AC power source (0–5A, 0–270 V, 50 Hz; AMETEK Model: EC 1000S). A multimeter was used to measure the cell voltage in order to calculate the power consumption during the needed treatment period.

The H<sub>2</sub>O<sub>2</sub>-DC/AC-EC procedure was implemented in the existing DC/AC-EC system by introducing H<sub>2</sub>O<sub>2</sub> externally. All studies were conducted at a constant temperature of 35 ± 1°C. At predefined time intervals, samples were taken from the reactor and centrifuged (REMI, Model: R-24) for 15 min at 15,000 rpm before being tested for COD and colour removal.

## 2.3 | Analysis

### 2.3.1 | Elimination effectiveness (%)

The effectiveness of the removal (%) was calculated using the colour and COD of industrial wastewater before and after the H<sub>2</sub>O<sub>2</sub>, DC/AC-EC, and H<sub>2</sub>O<sub>2</sub>-DC/AC-EC treatment processes. The COD and colour were measured using the closed reflux technique (Spectroquant TR 320) and a UV/Vis-Spectrophotometer (Spectroquant Pharo 300), adhering closely to the APHA standard method.<sup>[42]</sup>

Equations (8) and (9) were used to calculate the effectiveness of % colour and % COD elimination.

$$\begin{aligned} &\text{Efficiency of colour elimination, (\%)} \\ &= \left( \frac{Abs_i - Abs_t}{Abs_i} \right) * 100 \end{aligned} \quad (8)$$

where  $Abs_i$  and  $Abs_t$  are the absorbance of industrial wastewater before and after treatment at a constant wavelength ( $\lambda_{max}$ ).

$$\begin{aligned} &\text{Efficiency of COD elimination, (\%)} \\ &= \left( \frac{COD_i - COD_t}{COD_i} \right) * 100 \end{aligned} \quad (9)$$

where  $COD_i$  and  $COD_t$  are the COD (mg/L) of industrial wastewater before and after treatment, respectively.

### 2.3.2 | Consumption of power

Consumption of power is a significant issue in the H<sub>2</sub>O<sub>2</sub>-DC/AC-EC process, both practically and economically<sup>[26,43]</sup> and it was calculated using Equation (10).

$$\text{Consumption of power} = \left( \frac{VIt}{V_R} \right), \text{ kWh/m}^3 \quad (10)$$

where  $V$ —voltage (Volt),  $I$ —current (Amp),  $t$ —DC/AC-EC TT (h) and  $V_R$ —quantity of wastewater utilized (L).

### 2.3.3 | Synergistic effect

The presence of an SE is a crucial factor that contributes to the acceleration of the development of a hybrid approach to the treatment of industrial wastewater. When two or more processes, variables, etc. are combined, the combined impact is greater than the sum of their separate effects. The SE was computed using Equation (11), which compares the H<sub>2</sub>O<sub>2</sub>-AC-EC ( $X_{H_2O_2-AC-EC}$ ) % COD elimination efficiency

to the total of the COD elimination efficiency of the two-component processes, such as H<sub>2</sub>O<sub>2</sub> ( $X_{H_2O_2}$ ) and AC-EC ( $X_{AC-EC}$ ).<sup>[44]</sup>

$$SE = \left( \left( \frac{X_{H_2O_2-AC-EC}}{X_{H_2O_2} + X_{AC-EC}} \right) - 1 \right) * 100 \quad (11)$$

when the SE value is more than zero, there is a beneficial SE.

### 2.3.4 | Designing of experiments to optimize parameters

A standard RSM design known as CCD was utilized in order to conduct the evaluations necessary to determine the efficiency of colour and COD elimination (%), as well as consumption of power.<sup>[28,45]</sup> In experiments designed using a CCD for five independent variables, the variance of the predicted percentage elimination as a response,  $Y$ , at certain sites of independent variables,  $X$ , is merely a function of the point's distance from the design centre. The experiment design is used to organize studies using various combinations of independent variables and to reduce the number of runs. As independent variables, H<sub>2</sub>O<sub>2</sub> (A), Current (B), pH (C), COD (D) and TT (E) were selected.

Table 1 shows the levels employed in the experiments. Table 1 shows the experimental design matrix developed by the CCD, which has 50 sets of coded conditions with natural values. A two-level complete factorial design with 32 fact points ( $2^5 = 32$ ), eight centre points, and 10 axial points is used. On the acquired data, the Design of Expert Version 13 (Stat-Ease) was used to perform regression and graphical analysis. By solving the regression equation and examining the response surface contour plots and 3D, the optimum values of the given variables were determined. The multiple coefficients of determination,  $R^2$ , defined the variability in dependent variables, and the model equation was used to forecast the optimal value and then to highlight the interaction between the elements within the specified range.

### 2.3.5 | Mathematical modeling

The CCD was used to optimize efficiency COD elimination and consumption of power by the H<sub>2</sub>O<sub>2</sub>-AC-EC process for IW, as well as to assess the impacts and interactions of process factors. The response of COD elimination, (%) ( $Y_1$ ) and power consumption ( $Y_2$ ) as a function of independent variables with interactions were predicted by the RSM using a quadratic polynomial equation. Equation (12) for

the 2<sup>nd</sup>-order polynomial is written as follows.<sup>[46,47]</sup>

$$Y = \beta_0 + \sum_{j=1}^k \beta_j X_j + \sum_{j=1}^k \beta_{jj} X_j^2 + \sum_{j=1}^{k-1} \sum_{i=2}^k \beta_{ji} X_j X_i + \varepsilon_i \quad (12)$$

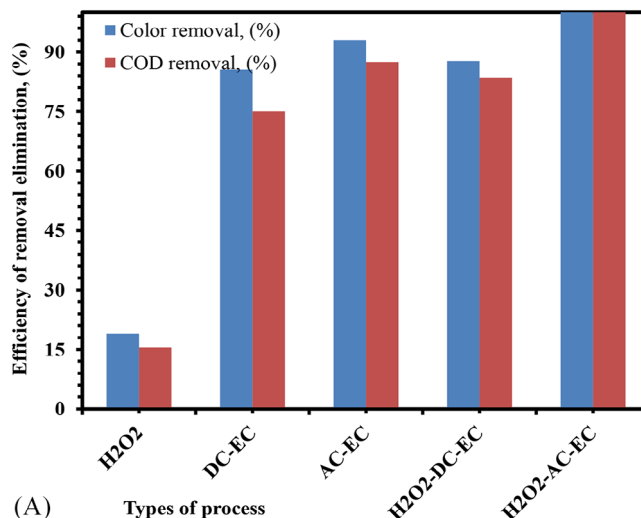
where  $Y$  is the predicted response,  $X_1, X_2, X_3, X_4$  and  $X_5$  are the operational variables,  $\beta_0$  is a constant,  $\beta_j, \beta_{ji}$  and  $\beta_{jj}$  are the interaction coefficients of linear, quadratic, and second-order terms and  $\varepsilon_i$  is the error. The value of correlation coefficients ( $R^2$ ) was used to describe the quality of the fit of the quadratic model, and significance was tested using the  $F$ -test in this program. The model was developed using 95% confidence levels on the variables.

### 3 | RESULTS AND DISCUSSION

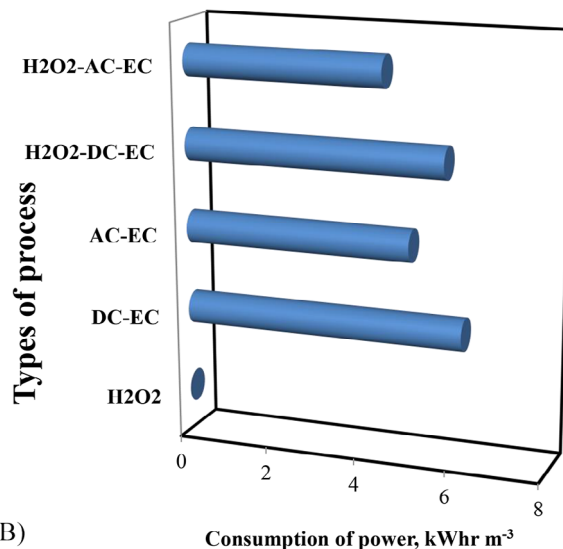
#### 3.1 | H<sub>2</sub>O<sub>2</sub>, DC/AC-EC and H<sub>2</sub>O<sub>2</sub>-DC/AC-EC process comparison

The H<sub>2</sub>O<sub>2</sub>, DC-EC, AC-EC, H<sub>2</sub>O<sub>2</sub>-DC-EC and H<sub>2</sub>O<sub>2</sub>-AC-EC processes were compared in terms of efficiency of colour and COD elimination (%), as well as consumption of power from the IW, in the first portion of the research, and the findings are shown in Figure 2A. As can be seen in Figure 2A, the H<sub>2</sub>O<sub>2</sub>-AC-EC method had the most performance in removing both colour and COD at a rate of 100% and following the decreasing sequence of H<sub>2</sub>O<sub>2</sub>-AC-EC > H<sub>2</sub>O<sub>2</sub>-DC-EC > AC-EC > DC-EC > H<sub>2</sub>O<sub>2</sub> process. The findings revealed that after 3 h of reaction time, the percentage of colour and COD removal efficiency was removed. Based on these discoveries, the H<sub>2</sub>O<sub>2</sub>-AC-EC technology can generate hydroxyl and other chemical oxidants concurrently via different processes. These high oxidant species increase pollutant removal by (i) accelerating anode dissolution by chemical oxidation and (ii) enhancing pollutant abatement through the oxidation action of radical species.<sup>[19,30,31,41]</sup>

When it comes to the employment of electrochemical and AOP technologies for the removal of pollutants from wastewater, the amount of energy that is consumed is an extremely vital and significant component. On the basis of the efficiency of COD elimination, the consumption of power was computed using Equation (10), and the results are shown in Figure 2B. As can be seen in Figure 2B, the consumption of power was around 0, 6.15, 5, 5.75 and 4.41 kWh m<sup>-3</sup> for the H<sub>2</sub>O<sub>2</sub> alone, DC-EC and AC-EC alone, H<sub>2</sub>O<sub>2</sub>-DC-EC and H<sub>2</sub>O<sub>2</sub>-AC-EC, respectively. According to the findings, it is clear that the H<sub>2</sub>O<sub>2</sub>-AC-EC process required a power input of 4.41 kWhm<sup>-3</sup> in order to remove



(A)



(B)

FIGURE 2 Comparison of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), DC-EC, AC-EC, H<sub>2</sub>O<sub>2</sub>-DC-EC and H<sub>2</sub>O<sub>2</sub>-AC-EC process on (a) efficiency of colour and chemical oxygen demand (COD) elimination, (%) and (b) consumption of power, (H<sub>2</sub>O<sub>2</sub> = 480 mg/L, PDC = 0.6, current = 0.7, pH = 5, COD = 3200 mg/L, distance between electrodes = 1 cm, combination of electrodes = Fe/Fe, TT = 3 h).

100% of the colour and 100% of the COD from IW. The treated IW was tested using local public health reuse criteria, and the findings demonstrated that the water is safe for both public and environmental health.

#### 3.2 | Central composite design

The impact of process variables in the H<sub>2</sub>O<sub>2</sub>-AC-EC process on outcomes like the efficiency of COD elimination and consumption of power were assessed and optimized using a 5-factor and level CCD. Fifty independent tests

were carried out, each with five distinct parameters. In the design centre, a total of forty-two experiments were conducted in a randomized sequence, with eight replications added for the purpose of quantifying pure error, as mandated by various design methodologies. Table 2 displays the number of runs, experimental settings, responses such as COD elimination (%), and consumption of power, as well as the predicted value.

### 3.2.1 | Analyzing experimental findings in relation to experiment design

The  $H_2O_2$  (A), Current (B), pH (C), COD (D), and TT (E) are functions of efficiency of COD elimination ( $Y_1$ ) and consumption of power ( $Y_2$ ), which is shown in Equations (13) and (14), respectively.

$$\begin{aligned}
 &\text{Efficiency of COD elimination, (\%)} Y_1 \\
 &= 70.12 + 2.75A + 16.18B - 2.02C - 7.12D + 13.79E \\
 &\quad - 0.33AB - 0.26AC - 0.22AD - 0.29AE - 1.09BC \\
 &\quad - 1.35BD + 0.22BE - 0.21CD + 0.51CE + 1.34DE \\
 &\quad + 2.98A^2 - 4.27B^2 - 9.96C^2 - 4.77D^2 - 3.74E^2
 \end{aligned} \tag{13}$$

$$\begin{aligned}
 &\text{Consumption of power, (kWhm}^{-3}\text{)}, Y_2 \\
 &= 2.99 - 0.17A + 0.67B + 0.02C - 0.20D + 0.64E \\
 &\quad - 0.10AB - 0.01AC + 0.05AD - 0.02AE - 0.12BC \\
 &\quad + - 0.01BD - 0.03BE + 0.08CD + 0.04CE \\
 &\quad + 0.2 \times 10^{-3}DE - 0.11A^2 - 0.10B^2 - 0.22C^2 \\
 &\quad - 0.12D^2 - 0.16E^2
 \end{aligned} \tag{14}$$

Two different tests, sequential model sum of squares and model summary statistics, were used to analyze the generated CCD experimental data in order to determine which of the various models—quadratic, 2FI, cubic, and linear—were the most efficient regression models. Tables 3 and 4 provide the findings for the COD elimination and the amount of power required, respectively. Tables 3 and 4 show that the  $R^2$ , *adjusted*  $R^2$ , and *predicted*  $R^2$  for the quadratic models are the highest of all of the models tested. As the cubic model was shown to be aliased, it cannot be utilized to represent experimental data in the future. When a model is aliased, insufficient experiments have been performed to allow for the independent estimation

of all of the models' terms. Certain parameters cannot be estimated independently whenever there are fewer independent design points than there are model terms. When a model is aliased, it should not be used for future studies. The sequential model sum of squares revealed that the  $p$ -values for the linear and quadratic models were both less than 0.0001. As a result, future studies might be done using both of them. The quadratic model was determined to have the highest "*adjusted*  $R^2$ " and "*predicted*  $R^2$ " values, according to the model summary statistics, which excluded the cubic model that was aliased.

A similar investigation was performed on the consumption of power, and the findings are shown in Table 4. In order to describe the impacts of process variables on IW treatment utilizing the  $H_2O_2$ -AC-EC process, the quadratic model was used.

### 3.2.2 | Model adequacy evaluated in terms of consumption of power and COD elimination efficiency

In order to assess the significance and adequacy of the model, analysis of variance (ANOVA) was employed and the resulting tables are presented in Tables 5 and 6. The regression model F-tests revealed extremely low  $p$ -values ( $< 0.0001$ ), suggesting that both models were highly significant. The model determination coefficients ( $R^2$ ) suggested that the models for COD elimination and consumption of power could explain 99.61 % and 98.72 % of the total variability, respectively. Moreover, the adjusted determination coefficients (*adjusted*  $R^2 = 0.99$  and 0.97) demonstrated the significant importance of COD removal and power consumption. Tables 5 and 6 provide the values of all regression coefficients together with their significance levels. The linear coefficients of  $H_2O_2$  (A), current (B), pH (C), COD (D) and TT (E), the interaction effect of current (B) with pH (C) and current (B) with COD (D), and COD (D) with TT (E) and the quadratic coefficient of  $H_2O_2$  (A), current (B), pH (C), COD (D) and TT (E) were found to be significant factors at a level less than 5% for COD elimination. Regarding consumption of power (Table 6), The linear coefficients of  $H_2O_2$  (A), current (B), COD (D) and TT (E), the interaction impact of current (B) with pH (C) and pH (C) with COD (D) and quadratic coefficient of  $H_2O_2$  (A), current (B), pH (C), COD (D) and TT (E) were significant factors. When measuring signal-to-noise ratio, "adeq accuracy" yields a desirable result larger than 4. For COD removal and power consumption, the current investigation found an appropriate signal-to-noise ratio of 68.61 and 41.12, respectively. As a result, the quadratic model might be utilized to investigate potential solutions.

**TABLE 2** Experimental design matrix and response based on the experimental runs and predicted values on the efficiency of chemical oxygen demand (COD) elimination, (%) and consumption of power proposed by CCD.

Run	Factor 1 A:H <sub>2</sub> O <sub>2</sub> mg/L	Factor 2 B:Current Amp	Factor 3 C:pH –	Factor 4 D:COD mg/L	Factor 5 E:TT h	Efficiency of COD elimination, (%)		Consumption of power kWh m <sup>-3</sup>	
						Actual	Predicted	Actual	Predicted
						1	480	0.28	9
2	360	0.42	11	4800	2	25	26.23	2.15	2.15
3	240	0.56	5	3200	2.5	84.25	87.45	4.30	4.21
4	240	0.28	5	6400	2.5	40.50	41.12	1.80	1.82
5	240	0.56	9	6400	2.5	68.40	68.93	3.50	3.61
6	480	0.28	5	6400	1.5	17.50	18.52	0.45	0.55
7	240	0.56	9	6400	1.5	38.50	36.65	2.30	2.34
8	360	0.42	7	4800	2	70	70.12	2.95	2.99
9	480	0.56	5	6400	1.5	48.75	49.28	2.05	1.95
10	480	0.56	9	6400	1.5	42.25	41.11	1.75	1.81
11	480	0.28	5	6400	2.5	47.55	46.77	1.65	1.85
12	480	0.28	9	6400	1.5	15.60	14.72	0.80	0.89
13	360	0.14	7	4800	2	22	20.66	1.40	1.26
14	480	0.28	9	6400	2.5	45.75	44.99	2.25	2.35
15	360	0.42	7	4800	2	70	70.12	2.95	2.99
16	360	0.42	7	4800	2	70	70.12	2.95	2.99
17	600	0.42	7	4800	2	90	87.52	2.40	2.22
18	240	0.28	5	3200	2.5	50	49.11	2.40	2.45
19	360	0.42	7	4800	1	25	27.57	1.15	1.07
20	360	0.7	7	4800	2	85	85.39	4.05	3.95
21	240	0.56	5	3200	1.5	62.60	62.56	3.08	3.11
22	240	0.28	9	6400	2.5	40	40.37	2.50	2.37
23	360	0.42	7	8000	2	35	36.79	2.25	2.11
24	360	0.42	7	4800	2	70	70.12	2.95	2.99
25	360	0.42	7	4800	2	70	70.12	3.05	2.99
26	480	0.28	5	3200	1.5	32.80	32.76	1.05	0.99
27	480	0.56	5	6400	2.5	78.25	78.40	3.25	3.15
28	240	0.28	9	6400	1.5	10.50	8.95	1.08	0.99
29	360	0.42	7	4800	2	70	70.12	2.95	2.99
30	480	0.56	9	3200	2.5	89	87.35	3.20	3.33
31	240	0.56	9	3200	1.5	55.28	56.25	2.85	2.70
32	360	0.42	3	4800	2	36.50	34.32	2.30	2.06
33	240	0.28	5	3200	1.5	25.64	25.09	1.20	1.23
34	240	0.28	9	3200	1.5	23.75	23.15	1.15	1.30
35	480	0.56	5	3200	1.5	69.75	68.93	2.25	2.44
36	480	0.28	9	3200	1.5	29.64	29.79	1.00	1.00
37	240	0.28	9	3200	2.5	48	49.19	2.50	2.67
38	240	0.56	5	6400	1.5	45.50	43.79	2.30	2.42
39	360	0.42	7	1600	2	68	65.26	3.00	2.90
40	120	0.42	7	4800	2	75	76.53	2.95	2.90
41	480	0.56	5	3200	2.5	91	92.67	3.50	3.64
42	360	0.42	7	4800	2	70	70.12	2.95	2.99

(Continues)

TABLE 2 (Continued)

Run	Factor 1 A:H <sub>2</sub> O <sub>2</sub>	Factor 2 B:Current	Factor 3 C:pH	Factor 4 D:COD	Factor 5 E:TT	Efficiency of COD elimination,		Consumption of power	
						(%)		kWh m <sup>-3</sup>	
43	480	0.28	5	3200	2.5	53	55.63	2.25	2.29
44	240	0.56	5	6400	2.5	75	74.05	3.40	3.53
45	480	0.56	9	3200	1.5	60.50	61.59	2.00	1.98
46	360	0.42	7	4800	2	70	70.12	2.95	2.99
47	240	0.56	9	3200	2.5	85	83.16	4.00	3.96
48	360	0.42	7	4800	3	86.25	82.73	3.80	3.64
49	480	0.56	9	6400	2.5	70	72.25	3.20	3.17
50	240	0.28	5	6400	1.5	10.50	11.72	0.60	0.59

TABLE 3 Sequential model sum of squares and model summary statistics for efficiency of chemical oxygen demand (COD) elimination, (%).

Sequential model sum of squares						
Source	Sum of squares	df	Mean square	F-value	p-value	
Mean versus Total	1.474E+05	1	1.474E+05			
Linear versus Mean	20574.62	5	4114.92	32.93	< 0.0001	
2FI versus Linear	175.21	10	17.52	0.1119	0.9996	
<b>Quadratic versus 2FI</b>	<b>5220.54</b>	<b>5</b>	<b>1044.11</b>	<b>294.51</b>	<b>&lt; 0.0001</b>	<b>Suggested</b>
Cubic versus Quadratic	89.91	15	5.99	6.50	0.0006	Aliased
Residual	12.90	14	0.9216			
Total	1.735E+05	50	3469.87			
Model summary statistics						
Source	Std. dev.	R <sup>2</sup>	Adjusted R <sup>2</sup>	Predicted R <sup>2</sup>	PRESS	
Linear	11.18	0.7891	0.7651	0.7444	6665.60	
2FI	12.51	0.7958	0.7058	0.7079	7617.24	
<b>Quadratic</b>	<b>1.88</b>	<b>0.9961</b>	<b>0.9933</b>	<b>0.9848</b>	<b>397.36</b>	<b>Suggested</b>
Cubic	0.9600	0.9995	0.9983	0.9755	637.92	Aliased

TABLE 4 Sequential model sum of squares and model summary statistics for consumption of power, kWh m<sup>-3</sup>.

Sequential model sum of squares						
Source	Sum of squares	df	Mean square	F-value	p-value	
Mean versus Total	294.56	1	294.56			
Linear versus Mean	37.41	5	7.48	62.67	< 0.0001	
2FI versus Linear	1.19	10	0.1191	0.9969	0.4652	
<b>Quadratic versus 2FI</b>	<b>3.52</b>	<b>5</b>	<b>0.7031</b>	<b>37.29</b>	<b>&lt; 0.0001</b>	<b>Suggested</b>
Cubic versus Quadratic	0.3431	15	0.0229	1.57	0.2021	Aliased
Residual	0.2037	14	0.0146			
Total	337.23	50	6.74			
Model Summary Statistics						
Source	Std. Dev.	R <sup>2</sup>	Adjusted R <sup>2</sup>	Predicted R <sup>2</sup>	PRESS	
Linear	0.3455	0.8769	0.8629	0.8501	6.40	
2FI	0.3457	0.9048	0.8628	0.8286	7.31	
<b>Quadratic</b>	<b>0.1373</b>	<b>0.9872</b>	<b>0.9783</b>	<b>0.9526</b>	<b>2.02</b>	<b>Suggested</b>
Cubic	0.1206	0.9952	0.9833	0.4602	23.03	Aliased

TABLE 5 ANOVA for a quadratic model for efficiency of chemical oxygen demand (COD) elimination, (%).

ANOVA for quadratic model						
Response 1: COD						
Source	Sum of squares	df	Mean square	F-value	p-value	
Model	25970.37	20	1298.52	366.26	< 0.0001	Significant
A-H <sub>2</sub> O <sub>2</sub>	301.79	1	301.79	85.12	< 0.0001	Significant
B-Current	10476.55	1	10476.55	2955.05	< 0.0001	Significant
C-pH	163.50	1	163.50	46.12	< 0.0001	Significant
D-COD	2026.49	1	2026.49	571.60	< 0.0001	Significant
E-TT	7606.29	1	7606.29	2145.46	< 0.0001	Significant
AB	3.40	1	3.40	0.9589	0.3356	
AC	2.13	1	2.13	0.5999	0.4449	
AD	1.52	1	1.52	0.4282	0.5180	
AE	2.63	1	2.63	0.7412	0.3963	
BC	38.22	1	38.22	10.78	0.0027	Significant
BD	58.46	1	58.46	16.49	0.0003	Significant
BE	1.51	1	1.51	0.4258	0.5192	
CD	1.37	1	1.37	0.3875	0.5385	
CE	8.17	1	8.17	2.30	0.1398	
DE	57.81	1	57.81	16.31	0.0004	Significant
A <sup>2</sup>	283.47	1	283.47	79.96	< 0.0001	Significant
B <sup>2</sup>	584.46	1	584.46	164.86	< 0.0001	Significant
C <sup>2</sup>	3175.21	1	3175.21	895.61	< 0.0001	Significant
D <sup>2</sup>	729.22	1	729.22	205.69	< 0.0001	Significant
E <sup>2</sup>	448.19	1	448.19	126.42	< 0.0001	Significant
Residual	102.81	29	3.55			
Lack of fit	102.81	22	4.67			
Pure error	0.0000	7	0.0000			
Cor total	26073.18	49				

\*df—degrees of freedom.

### 3.2.3 | Actual versus predicted

The analytical procedure includes an essential step called the proposed model's adequacy check. In order to prevent inaccurate or misleading outcomes, adequate adequacy ensures that the approximating model provides a suitable approximation. Table 2 and Figure 3A,B provide a comparison of the actual and predicted values from the model. The model predictions were found to match the experimental values, and the data points were found to be close to the diagonal line. For these two quadratic equations, the regression model's analysis of variance was very significant ( $p < 0.0001$ ). The analysis demonstrated that the COD elimination and consumption of power by the H<sub>2</sub>O<sub>2</sub>-AC-EC process could be satisfactorily predicted using these second-order polynomial equations. The determination of the regression coefficients  $R^2$  confirmed the quadratic equation's suitability of fit. The quadratic equations had

$R^2$  values of 0.9961 and 0.9872 for COD elimination and consumption of power, respectively.

### 3.2.4 | Normal probability

The internally studentized residuals calculated the standard deviations between the actual and predicted values, whereas the residuals showed how well the model met the ANOVA assumptions. Figure 4A,B illustrates the results of an examination of the data to determine if the residuals were normally distributed. The normal % probability plots of the studentized residuals for (a) COD elimination and (b) power consumption utilizing the H<sub>2</sub>O<sub>2</sub>-AC-EC method are displayed in Figure 4A,B. If the residuals are normally distributed and will plot as a straight line, this is indicated by a normal probability plot.<sup>[1,48,49]</sup> Even with normalized data, some scattering is to be expected. Figure 4A,B thus demonstrates the regular distribution of the data.

TABLE 6 ANOVA for a quadratic model for consumption of power, kWh m<sup>-3</sup>.

ANOVA for quadratic model						
ANOVA for quadratic model Source	ANOVA for quadratic model Sum of squares	ANOVA for quadratic model df	ANOVA for quadratic model Mean square	ANOVA for quadratic model F-value	ANOVA for quadratic model p-value	
Model	42.12	20	2.11	111.70	< 0.0001	Significant
A-H <sub>2</sub> O <sub>2</sub>	1.16	1	1.16	61.49	< 0.0001	Significant
B-Current	18.16	1	18.16	963.03	< 0.0001	Significant
C-pH	0.0181	1	0.0181	0.9580	0.3358	
D-COD	1.58	1	1.58	83.80	< 0.0001	Significant
E-TT	16.50	1	16.50	875.09	< 0.0001	Significant
AB	0.3507	1	0.3507	18.60	0.0002	Significant
AC	0.0063	1	0.0063	0.3356	0.5668	
AD	0.0751	1	0.0751	3.98	0.0555	
AE	0.0158	1	0.0158	0.8355	0.3682	
BC	0.4536	1	0.4536	24.06	< 0.0001	Significant
BD	0.0053	1	0.0053	0.2786	0.6016	
BE	0.0226	1	0.0226	1.20	0.2828	
CD	0.2129	1	0.2129	11.29	0.0022	Significant
CE	0.0488	1	0.0488	2.59	0.1184	
DE	0.0001	1	0.0001	0.0041	0.9491	
A <sup>2</sup>	0.3780	1	0.3780	20.05	0.0001	Significant
B <sup>2</sup>	0.2961	1	0.2961	15.70	0.0004	Significant
C <sup>2</sup>	1.57	1	1.57	83.03	< 0.0001	Significant
D <sup>2</sup>	0.4700	1	0.4700	24.93	< 0.0001	Significant
E <sup>2</sup>	0.8058	1	0.8058	42.74	< 0.0001	Significant
Residual	0.5468	29	0.0189			
Lack of fit	0.5380	22	0.0245	19.56	0.0003	Significant
Pure error	0.0087	7	0.0012			
Cor total	42.67	49				

\*df—degrees of freedom.

### 3.2.5 | Combined impact of operational factors on consumption of power and COD elimination efficiency

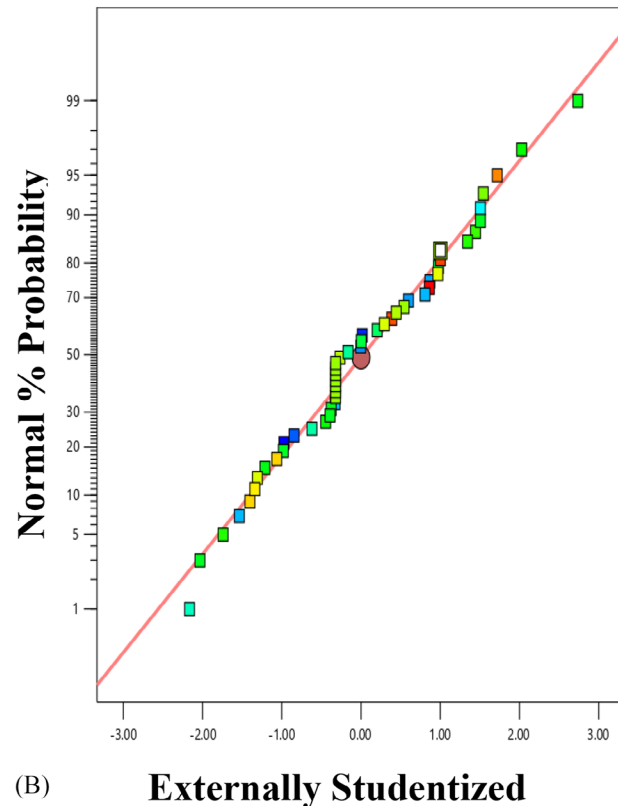
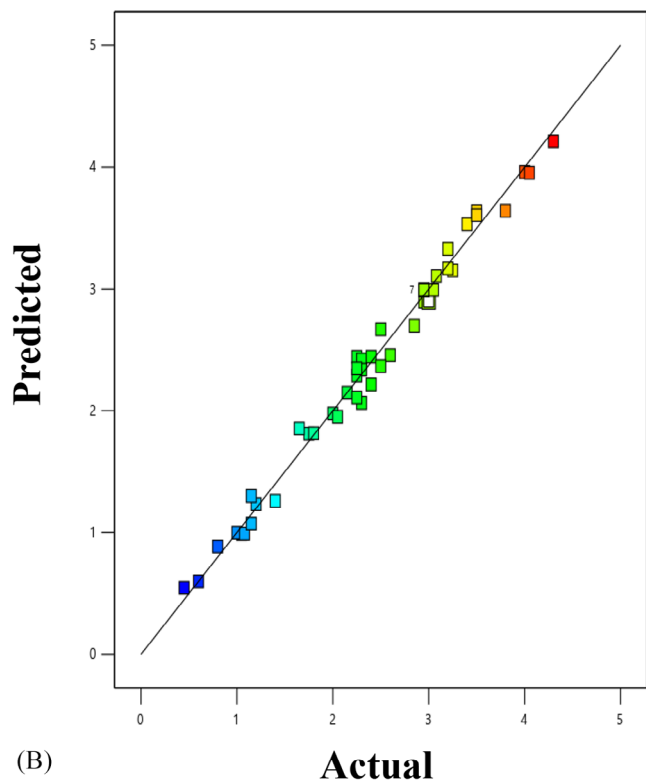
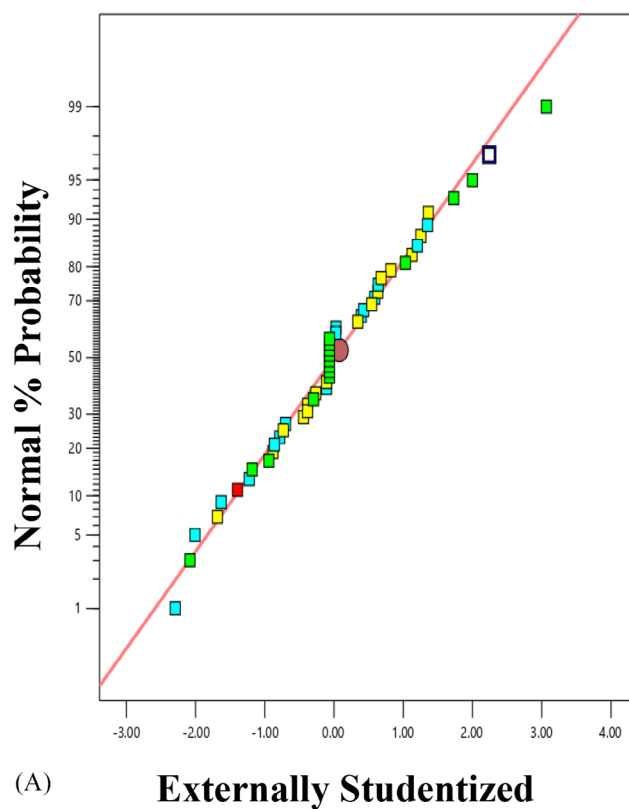
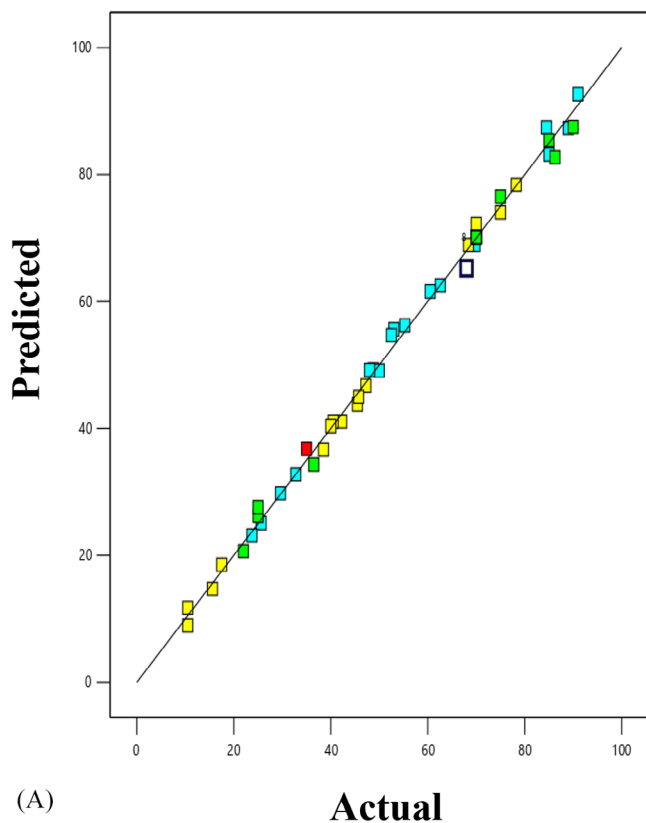
The effects of each variable on COD elimination efficiency and power consumption are displayed in Figures 5A,B, 6A,B and 7A,B. Furthermore, the impact of operational parameters derived from response surface analysis is demonstrated in order to ascertain the lowest power consumption and highest COD removal effectiveness for each variable.

#### H<sub>2</sub>O<sub>2</sub> (A) versus Current (B)

In the H<sub>2</sub>O<sub>2</sub>-AC-EC process, the concentration of H<sub>2</sub>O<sub>2</sub> plays a significant role.<sup>[20,41]</sup> The concentration of H<sub>2</sub>O<sub>2</sub> was changed from 120 to 600 mg/L to investigate the influence of H<sub>2</sub>O<sub>2</sub> concentration (A) on COD elimination efficiency and consumption of power utilizing the H<sub>2</sub>O<sub>2</sub>-

AC-EC process, and the findings are shown in Figure 5A,B. By increasing A at any current (B) level, the effectiveness of COD removal increased while the consumption of power decreased. The reason for this is that there was inadequate generation of <sup>•</sup>OH when there was a lower concentration of H<sub>2</sub>O<sub>2</sub>, which resulted in a very slow elimination of COD. Since more <sup>•</sup>OH was formed as a result of the higher H<sub>2</sub>O<sub>2</sub> concentration, the quantity of COD that was removed from the water also increased.<sup>[50]</sup>

The amount of <sup>•</sup>OH generated and the reaction rate are both influenced by current (B), which is a crucial component of the electrochemical process.<sup>[20,51,52]</sup> The applied current has a significant impact on both the consumption of power and the effectiveness of pollutant removal.<sup>[53]</sup> Current (B) was varied from 0.14 to 0.7 Amp under different initial A ranging from 120 to 600 mg/L to examine the combined effects of B and A on COD elimination efficiency and consumption of power. The data is shown in



**FIGURE 3** Relationship between actual and predicted value for (A) efficiency of chemical oxygen demand (COD) elimination, (%) and (B) consumption of power,  $\text{kWh m}^{-3}$ .

**FIGURE 4** Plot for the relationship between normal % probability and external studentized residuals for (A) efficiency of chemical oxygen demand (COD) elimination, (%) and (B) consumption of power,  $\text{kWh m}^{-3}$ .

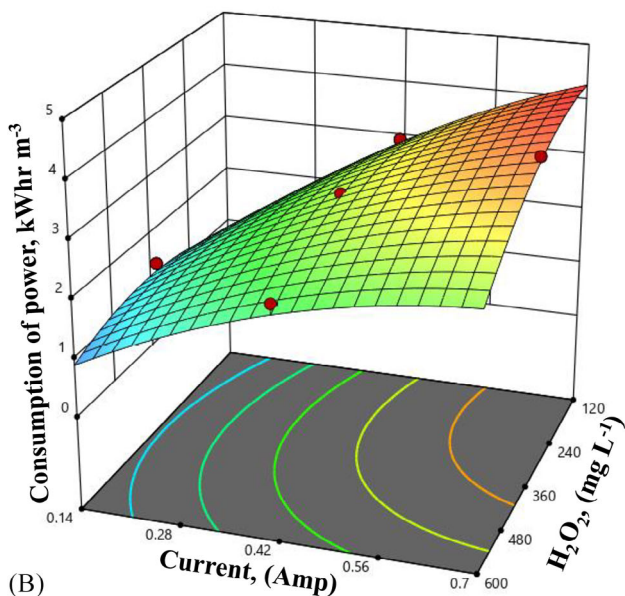
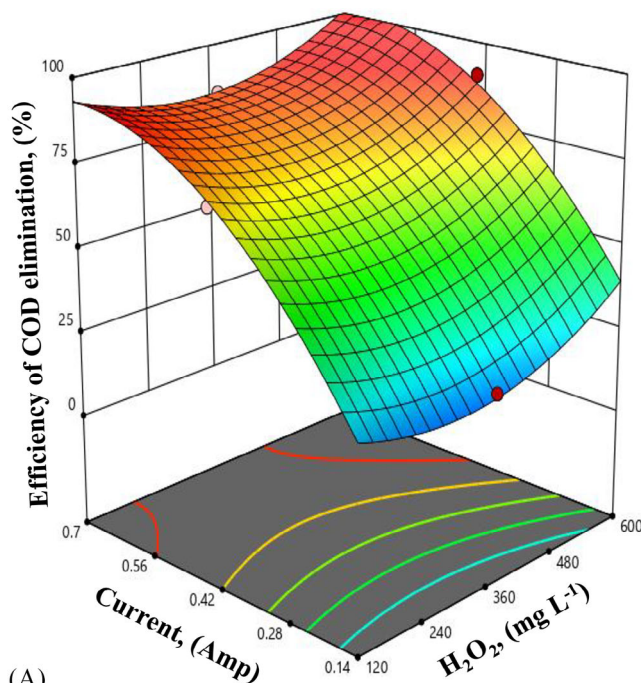


FIGURE 5 Response surface plots for the effects of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) (A) and Current (B) on (A) efficiency of chemical oxygen demand (COD) elimination, (%) and (B) consumption of power (pH = 7, COD = 4800 mg/L and TT = 2 h).

Figure 5A,B and reported in Table 2. According to the figures, increasing B increased COD elimination efficiency and consumption of power at any initial A. This tendency may be explained by the production of more  $\cdot\text{OH}$  in the solution as the A increases.<sup>[54]</sup> The lower current value mandates a longer period for pollutant removal, necessitating larger facilities and higher operational costs. As a

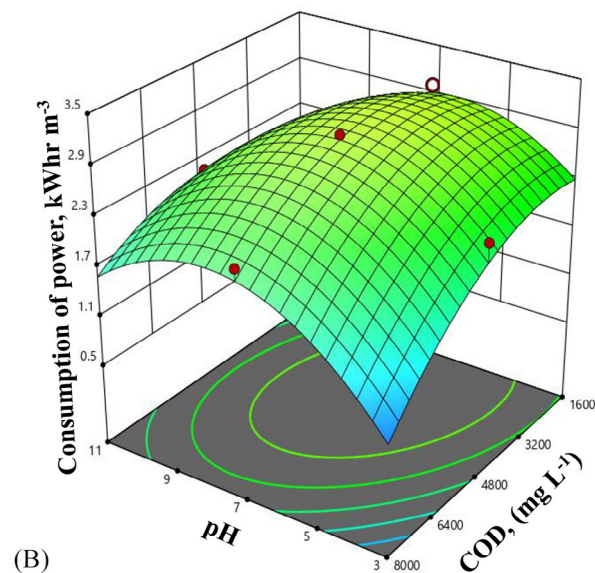
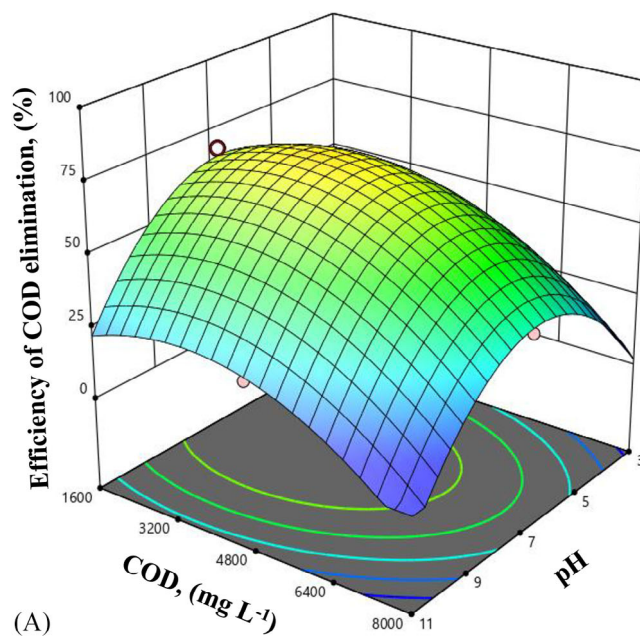
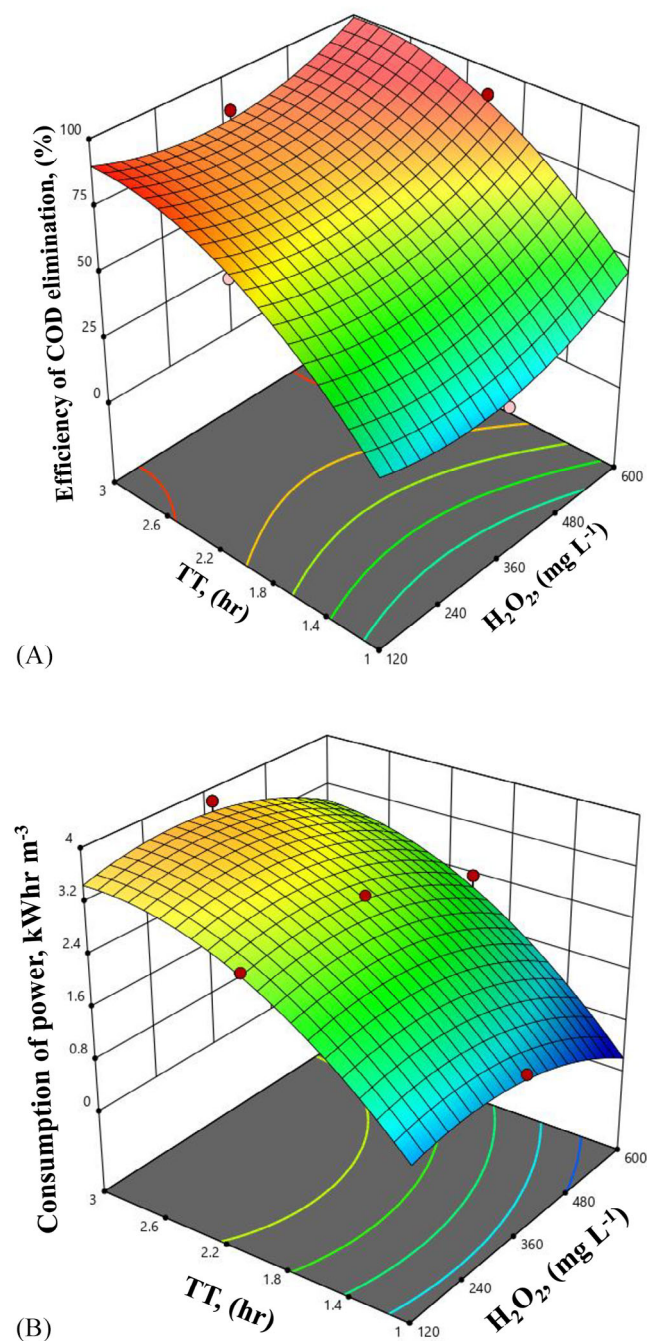


FIGURE 6 Response surface plots for the effects of pH (C) and chemical oxygen demand (COD) (D) on (A) efficiency of COD elimination, (%) and (B) consumption of power (hydrogen peroxide [ $\text{H}_2\text{O}_2$ ] = mg/L, Current = 0.42 Amp and TT = 2 h).

result, higher current values lead to energy loss from partial heating caused by electrical energy, as well as higher consumption of power and operating costs. As a result, the current should be optimized to improve pollutant removal effectiveness while using the least amount of power.

#### pH (C) versus COD (D)

Figure 6A,B shows the impacts of wastewater pH (C) on COD elimination efficiency and consumption of power using the  $\text{H}_2\text{O}_2$ -AC-EC process. The wastewater pH was



**FIGURE 7** Response surface plots for the effects of TT (E) and hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) (A) on (a) efficiency of chemical oxygen demand (COD) elimination, (%) and (b) consumption of power (Current = 0.42 Amp, pH = 7, COD = 4800 mg/L).

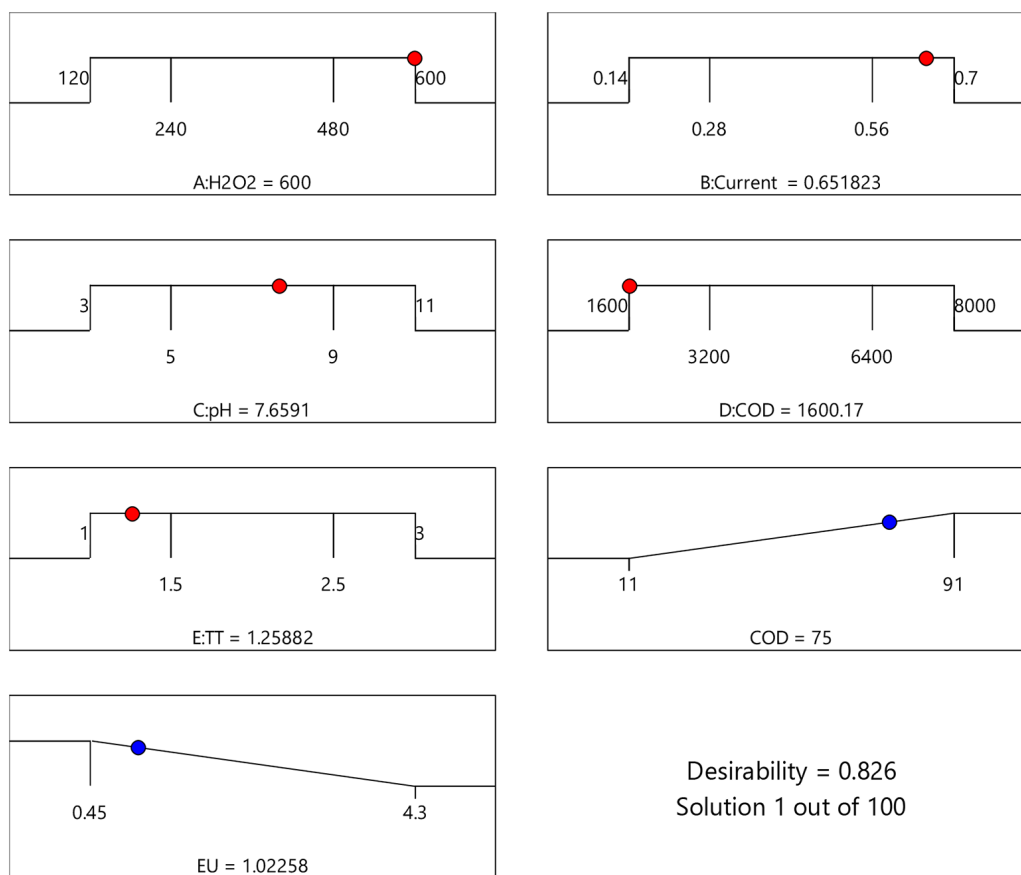
adjusted within the range of 3–11. The results demonstrated that for effluent pH values between 0 and 7, the efficacy of COD removal improved, but it declined values between pH values 7 and 11 at all COD (D). This phenomenon can be elucidated by the iron species generated by the reaction mechanism. The two most important electrochemical processes on the electrodes for the iron anode were known to be iron electro-dissolution (1) and water reduction (2).<sup>[41]</sup>

Monomeric hydroxometallic cations, such as  $\text{Fe}(\text{OH})_3$ , are the main species that develop in acidic environments. At mid-pH ranges, metal hydroxide precipitates and polymeric hydroxometallic cations dwell together. At higher pH levels, the polymeric hydroxometallic cations stay in the solution and the net charge on the surface of the precipitate of amorphous metal hydroxide shifts from positive to negative. Consequently, in alkaline media, monomeric hydroxometallic anions predominate ( $\text{Fe}(\text{H}_2\text{O})_6^{3+}$ ,  $\text{Fe}(\text{H}_2\text{O})_5(\text{OH})^{2+}$ ,  $\text{Fe}(\text{H}_2\text{O})_4(\text{OH})_2^+$ ,  $\text{Fe}(\text{H}_2\text{O})_8(\text{OH})_2^{4+}$  and  $\text{Fe}(\text{H}_2\text{O})_6(\text{OH})_4^{4+}$ ).<sup>[41]</sup> The major species for the operating conditions employed in this investigation were amorphous hydroxides. The results might be explained by assuming that the primary coagulation mechanism was the incorporation of pollutants into rising precipitates (sweep coagulation). In the  $\text{H}_2\text{O}_2$ -AC-EC process, neutral mediums produced more  $\cdot\text{OH}$  than acidic and alkaline mediums.<sup>[55]</sup>

Figure 6A,B shows the results of changing the IW of COD from 1600 to 8000 mg/L to explore the effect of COD concentration (D) on COD elimination efficiency and power consumption using the  $\text{H}_2\text{O}_2$ -AC-EC process. With any level of pH, the efficiency of COD removal and consumption of power decreased as COD concentration increased (D). One of the characteristics of electrochemical processes is this behaviour. Faraday's Law states that for any value of constant current (B) and treatment period (E), an increasing initial COD concentration results in the release of a constant amount of  $\text{Fe}^{2+}$  into the solution. As COD concentration increased in an electrolysis experiment, specific quantities of  $\cdot\text{OH}$  were produced. Notwithstanding, the quantity of  $\cdot\text{OH}$  produced was insufficient to decompose the high concentration of COD in IW.<sup>[56,57]</sup> In conclusion, the oxidizing efficiency declined as the COD concentration increased.

#### *TT (E) versus $\text{H}_2\text{O}_2$ (A)*

The TT of the electrochemical process is a critical factor in assessing their economic sustainability. According to Faraday's Law, the amount of iron released into the hybrid system through the Fe electrodes may change the residence duration, resulting in an increase in the number of Fe ions released into the system.<sup>[58,59]</sup> Figure 7A,B demonstrates the effects of TT (E) and  $\text{H}_2\text{O}_2$  (A) on COD elimination efficiency and consumption of power by the  $\text{H}_2\text{O}_2$ -AC-EC method. The studies were carried out by varying the TT (E) from 1 to 3 h while keeping the  $\text{H}_2\text{O}_2$  constant (A). Figure 7A,B indicates that increasing the TT (E) enhanced the COD removal efficiency and increased the consumption of power. This was primarily owing to the fact that as TT increased, more metal (iron) polymeric species were produced (E). As a consequence, more  $\cdot\text{OH}$  was generated,



**FIGURE 8** Optimization results of chemical oxygen demand (COD) elimination, (%) and consumption of power by hydrogen peroxide ( $\text{H}_2\text{O}_2$ )-AC-EC process.

which improved COD removal efficiency.<sup>[60]</sup> Figure 7B depicts the influence of TT (E) on the consumption of power. The consumption of power increased with TT, as seen in Figure 6B. Treatment time resulted in an increase in cell voltage, and power consumption was proportional to cell voltage.

### 3.3 | Optimization

The main objective of this study is to determine the most effective condition for maximizing the elimination of COD and decreasing the consumption of power in the treatment of IW utilizing the  $\text{H}_2\text{O}_2$ -AC-EC method. The response surface methodology (RSM) regression equation, derived from the CCD, was employed to optimize the results. Figure 8 shows the optimization results of the efficiency of COD elimination and consumption of power by the  $\text{H}_2\text{O}_2$ -AC-EC process. According to these results, the optimum process conditions for 75% COD elimination efficiency and 1.02  $\text{kWh m}^{-3}$  consumption of power were  $\text{H}_2\text{O}_2$  of 600 mg/L, current of 0.65, pH of 7.6, COD of 1600 mg/L and TT of 1.26 h. To verify the reliability of the model, ver-

ification experiments were carried out with 3 repetitions under these optimum process conditions. As a result of the experiments, the average COD elimination efficiency and consumption of power was found to be 79.75% and 1.10  $\text{kWh m}^{-3}$ . The reliability of the model was verified with a very low error margin of 0.90%.

### 3.4 | Synergistic effect of the combined process

The synergistic impact was evaluated using Equation (11) based on the percentage COD elimination efficiency for IW utilizing  $\text{H}_2\text{O}_2$  alone, AC-EC process alone, and hybrid  $\text{H}_2\text{O}_2$ -AC-EC techniques. It was discovered that the synergistic impact for the combined process ( $\text{H}_2\text{O}_2$ -AC-EC process) was 15.65%, which indicates that the synergy was positive. There are several benefits associated with the usage of the hybrid process that contributes to its increased removal efficiency. These advantages are as follows: (i)  $\text{H}_2\text{O}_2$  and electrical power play synergistic roles; (ii) there is no passive layer on the electrode's surface; and (iii) more hydroxyl radicals are produced.

## 4 | CONCLUSION

According to the findings of this study, the H<sub>2</sub>O<sub>2</sub>, DC/AC-EC and H<sub>2</sub>O<sub>2</sub>-DC/AC-EC technologies were employed to treat real industrial wastewater from distilleries. The percentage of color and COD eliminated, as well as the consumption of power were compared for each of these processes. In comparison to other treatment approaches, the combined H<sub>2</sub>O<sub>2</sub>-AC-EC process eliminated 100% of the colour and 100% of the COD with a consumption of power of 4.41 kWh m<sup>-3</sup>. Based on the experimental results, an empirical relationship between the response and the independent variables was constructed and described using a second-order polynomial equation. The model predicted response surface established the impacts of the experimental conditions on COD removal and power consumption of the industrial effluent. The coefficient of determination value in the analysis of variance was high, indicating that the second-order regression model was effectively matched with the experimental data. In addition, it has been proved that there is a SE that occurs when H<sub>2</sub>O<sub>2</sub> and AC-EC processes are combined. At the most favourable conditions for the process, the combined method revealed a synergistic impact that was 15.75 % positive. The study findings indicated that the H<sub>2</sub>O<sub>2</sub> process would be a desired and efficient technology for improving traditional AC EC technologies for wastewater and industrial effluent treatment.

### AUTHOR CONTRIBUTIONS

Perumal Asaithambi: Investigation; data curation; resources; writing—original draft.

Wendesen Mekonin Desta: Conceptualization; methodology; validation; supervision.

Mohammed Hussen: Formal Analysis; resources; supervision.

Mamuye Busier Yesuf: Investigation; data curation; formal analysis; resources.

Dejene Beyene: Conceptualization; methodology; validation; supervision.

### ACKNOWLEDGEMENTS

The authors are very thankful and acknowledge the administration of the Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Jimma, Ethiopia, Po Box – 378.

### CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

The authors do not have permission to share data.

## REFERENCES

1. A. A. Moneer, W. M. Thabet, M. Khedawy, M. M. El-Sadaawy, N. A. Shaaban, *Int. J. Environ. Sci. Technol.* **2023**, *20*, 13859.
2. A. G. Merma, B. F. Santos, A. S. C. Rego, R. R. Hacha, M. L. Torem, *J. Mater. Res. Technol.* **2020**, *9*, 15164.
3. M. Al-Shannag, Z. Al-Qodah, K. Alananbeh, N. Bouqellah, E. Assirey, K. Bani-Melhem, *Environ. Eng. Manag. J.* **2014**, *13*, 3153.
4. F. Ilhan, K. Ulucan-Altuntas, Y. Aversus ar, U. Kurt, A. Saral, *Front. Environ. Sci. Eng.* **2019**, *13*, 73.
5. N. M. Mahmoodi, A. Dalvand, *Desalin. Water Treat.* **2013**, *51*, 5959.
6. B. Chezeau, L. Boudriche, C. Vial, A. Boudjemaa, *Sep. Sci. Technol.* **2020**, *55*, 2510.
7. A. A. Mohamud, Y. Çalışkan, N. Bektaş, H. C. Yatmaz, *Sep. Sci. Technol.* **2018**, *53*, 2468.
8. S. Najari, M. Delnavaz, D. Bahrami, *Chem. Phys. Lett.* **2023**, *832*, 140897.
9. K. E. Adou, A. R. Kouakou, A. D. Ehouman, R. D. Tyagi, P. Drogui, K. Adouby, *Sci. African* **2022**, *16*, e01238.
10. F. Özyonar, M. U. Korkmaz, *Chemosphere* **2022**, *290*, 133172.
11. K. Thirugnanasambandham, V. Sivakumar, J. Prakash Maran, *Environ. Prog. Sustain. Energy* **2015**, *34*, 411.
12. M. A. A. Hamid, H. A. Aziz, M. S. Yusoff, in *Sustain. Solut. Environ. Pollut.*, **2021**, pp. 257.
13. Z. Qi, S. You, R. Liu, C. J. Chuah, *Front. Environ. Sci. Eng.* **2020**, *14*, 40.
14. I. Wysocka, W. Masalski, *Environ. Prog. Sustain. Energy* **2018**, *37*, 975.
15. A. Aygun, B. Nas, M. F. Sevimli, *Korean J. Chem. Eng.* **2019**, *36*, 1441.
16. F. Ozyonar, B. Karagozoglu, *Int. J. Environ. Sci. Technol.* **2012**, *9*, 637.
17. R. K. Patel, R. Shankar, P. Khare, P. Mondal, *J. Indian Chem. Soc.* **2022**, *99*, 100563.
18. Y. G. Asfaha, F. Zewge, T. Yohannes, S. Kebede, *Chemosphere* **2022**, *302*, 134706.
19. H. A. Alalwan, N. S. Mohammed Ali, M. M. Mohammed, M. F. Mohammed, A. H. Alminshid, *Clean. Eng. Technol.* **2023**, *13*, 100623.
20. A. R. Yazdanbakhsh, M. R. Massoudinegad, S. Eliasi, A. S. Mohammadi, *J. Water Process Eng.* **2015**, *6*, 51.
21. N. Modirshahla, M. A. Behnajady, S. Kooshaiian, *Dye. Pigment.* **2007**, *74*, 249.
22. F. Janpoor, A. Torabian, V. Khatibikamal, *J. Chem. Technol. Biotechnol.* **2011**, *86*, 1113.
23. B. yul Tak, B. sik Tak, Y. ju Kim, Y. jin Park, Y. hun Yoon, G. ho Min, *J. Ind. Eng. Chem.* **2015**, *28*, 307.
24. M. Eyvaz, *Int. J. Electrochem. Sci.* **2016**, *11*, 4988.
25. A. Othmani, A. Kesraoui, M. Seffen, *Euro-Mediterranean J. Environ. Integr.* **2017**, *2*, <https://doi.org/10.1007/s41207-017-0016-y>.
26. M. Alimohammadi, A. Mesdaghinia, M. H. Shayesteh, H. J. Mansoorian, N. Khanjani, *Int. J. Environ. Sci. Technol.* **2019**, *16*, 8239.
27. Y. Bian, Z. Ge, C. Albano, F. L. Lobo, Z. J. Ren, *Environ. Sci. Water Res. Technol.* **2019**, *5*, 1654.
28. A. Arabameri, M. R. Alavi Moghaddam, A. R. Azadmehr, M. Payami Shabestar, *Chem. Eng. Process.—Process Intensif.* **2022**, *174*, 108869.

29. E. Karamati-Niaragh, M. R. Alavi Moghaddam, M. M. Emamjomeh, E. Nazlabadi, *J. Environ. Manage.* **2019**, *230*, 245.
30. W. Zhang, M. Zhang, J. Yao, J. Long, *Arab. J. Chem.* **2023**, *16*, 104607.
31. V. K. Sandhwar, B. Prasad, *Korean J. Chem. Eng.* **2018**, *35*, 909.
32. S. Vasudevan, J. Lakshmi, G. Sozhan, *J. Hazard. Mater.* **2011**, *192*, 26.
33. H. J. Mansoorian, A. H. Mahvi, A. J. Jafari, *Sep. Purif. Technol.* **2014**, *135*, 165.
34. T. Xu, Y. Zhou, B. Hu, X. Lei, G. Yu, *Ecotoxicol. Environ. Saf.* **2020**, *197*, 110629.
35. P. Asaithambi, R. Govindarajan, M. B. Yesuf, P. Selvakumar, E. Alemayehu, *J. Environ. Chem. Eng.* **2021**, *9*, 104811.
36. L. Xu, Q. Huang, X. Xu, G. Cao, C. He, Y. Wang, M. Yang, *Sep. Purif. Technol.* **2017**, *188*, 316.
37. F. Rajaei, E. Taheri, S. Hadi, A. Fatehizadeh, M. M. Amin, N. Rafei, S. Fadaei, T. M. Aminabhavi, *Environ. Pollut.* **2021**, *277*, 116632.
38. E. Gatsios, J. N. Hahladakis, E. Gidarakos, *J. Environ. Manage.* **2015**, *154*, 117.
39. M. R. Samarghandi, A. Dargahi, A. Shabanloo, H. Z. Nasab, Y. Vaziri, A. Ansari, *Arab. J. Chem.* **2020**, *13*, 6847.
40. İ. A. Şengil, S. Kulaç, M. Özacar, *J. Hazard. Mater.* **2009**, *167*, 940.
41. S. Farhadi, B. Aminzadeh, A. Torabian, V. Khatibikamal, M. Alizadeh Fard, *J. Hazard. Mater.* **2012**, *219–220*, 35.
42. APHA, **2012**, 1496.
43. A. Dalvand, M. Gholami, A. Joneidi, N. M. Mahmoodi, *Clean—Soil, Air, Water* **2011**, *39*, 665.
44. Y.-Z. Ren, M. Franke, F. Anschuetz, B. Ondruschka, A. Ignaszak, P. Braeutigam, *Ultrason. Sonochem.* **2014**, *21*, 2020.
45. A. Kadier, J. Wang, K. Chandrasekhar, P. Abdesahian, M. A. Islam, F. Ghanbari, M. Bajpai, S. S. Katoch, P. B. Bhagawati, H. Li, M. S. Kalil, A. A. Hamid, H. Abu Hasan, P.-C. Ma, *Int. J. Hydrogen Energy* **2022**, *47*, 15464.
46. M. Darvishmotevalli, A. Zarei, M. Moradnia, M. Noorisepehr, H. Mohammadi, *MethodsX* **2019**, *6*, 1101.
47. G. K. Akkaya, *Chem. Eng. Res. Des.* **2022**, *187*, 261.
48. A. R. Khataee, M. Zarei, L. Moradkhannejhad, *DES* **2010**, *258*, 112.
49. U. Tezcan Un, A. Kandemir, N. Erginel, S. E. Ocal, *J. Environ. Manage.* **2014**, *146*, 245.
50. K. Thirugnanasambandham, S. Kandasamy, V. Sivakumar, R. K. kumar, R. Mohanavelu, *J. Taiwan Inst. Chem. Eng.* **2015**, *46*, 89.
51. N. Masomboon, C. Ratanatamskul, M.-C. Lu, *Appl. Catal. A Gen.* **2010**, *384*, 128.
52. S. Garcia-Segura, A. El-Ghenymy, F. Centellas, R. M. Rodríguez, C. Arias, J. A. Garrido, P. L. Cabot, E. Brillas, *J. Electroanal. Chem.* **2012**, *681*, 36.
53. E. Pajootan, M. Arami, M. Rahimdokht, *Ind. Eng. Chem. Res.* **2014**, *53*, 16261.
54. M. S. Çelebi, N. Oturan, H. Zazou, M. Hamdani, M. A. Oturan, *Sep. Purif. Technol.* **2015**, *156*, 996.
55. M. Saravanan, N. P. Sambhamurthy, M. Sivarajan, *Clean—Soil, Air, Water* **2010**, <https://doi.org/10.1002/clen.200900278>.
56. M. Sedaghat, B. Vahid, S. Aber, M. H. Rasoulifard, A. Khataee, N. Daneshvar, *Res. Chem. Intermed.* **2016**, *42*, 855.
57. J. Wu, W. Pu, C. Yang, M. Zhang, J. Zhang, *J. Environ. Sci.* **2013**, *25*, 801.
58. P. Maha Lakshmi, P. Sivashanmugam, *Sep. Purif. Technol.* **2013**, *116*, 378.
59. P. Asaithambi, M. B. Yesuf, R. Govindarajan, N. M. Hariharan, P. Thangavelu, E. Alemayehu, *J. Environ. Manage.* **2022**, *320*, 115926.
60. G. Divyapriya, R. Srinivasan, J. Mohanalakshmi, I. M. Nambi, *J. Water Process Eng.* **2022**, *49*, 102967.

**How to cite this article:** P. Asaithambi, W. M. Desta, M. Hussien, M. B. Yesuf, D. Beyene, *Electrochem. Sci. Adv.* **2024**, *4*, e2300029. <https://doi.org/10.1002/elsa.202300029>