

Downstream Processing of Palm Oil Mill Effluent in a CBME Reactor

Madhuri Damaraju¹; Debraj Bhattacharyya²; Tarun Kanti Panda³; and Kiran Kumar Kurilla⁴

Abstract: This study describes a laboratory-scale continuous-flow bipolar mode electrocoagulation (CBME) unit that was developed as a downstream process unit for polishing an anaerobically treated palm oil mill effluent (POME). The design of the CBME reactor has the advantage of achieving good treatment efficiency with lesser energy consumption when compared to monopolar electrocoagulation systems. The process optimization was carried out for maximum removal of total organic carbon (TOC) and total phosphorus (TP) using response surface methodology (RSM). The independent process variables selected are initial pH, retention time (RT), reaction area (RA), and current density (CD). The optimum condition was achieved when pH was set at 6.4, retention time at 7.7 min, reaction (electrode) area at 765 cm², and current density at 77.8 A/m². Under this condition, 77% and 73% of TOC and TP removals were observed, respectively. The ratio of the total surface area of electrodes to the volume of the reactor was found to be 76.5 m⁻¹ at the optimum operating condition. The energy consumption at the optimum point was 22.4 kW · h/m³ of wastewater treated. Micropollutants were screened for the organic constituents present before and after the treatment using high-resolution mass spectroscopy (HRMS). DOI: 10.1061/(ASCE)JZ.2153-5515.0000484. © 2019 American Society of Civil Engineers.

Author keywords: Bipolar mode electrocoagulation; Industrial wastewater; Optimization; Palm oil mill effluent; Wastewater treatment.

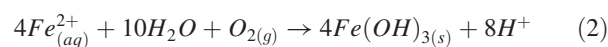
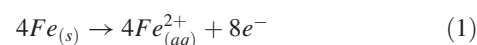
Introduction

Downstream wastewater treatment systems are needed to remove residual organic matter and nutrients from wastewaters after biological treatment. Palm oil mill effluent (POME) is generated in high volumes and has a very high organic content and nutrients. Biological treatment is not adequate to remove the recalcitrant organics present in the water. Therefore, there is a need for industries to adopt polishing systems after biological treatment, which can efficiently remove the residual organic carbon. Phosphorus is a valuable and nonrenewable limited resource in the world. POME being agro-industrial wastewater, has high concentration of phosphorus that can be recovered with the treatment of wastewater. Several physicochemical treatment methods have been deployed for downstream processing of POME including membrane filtration processes and advanced oxidation processes for removal of organics and color (Ahmad et al. 2006; Liew et al. 2014). There is a pressing need for cost-effective technology with better removal of pollutants for POMEs. Electrochemical methods are gaining importance in the current scenario due to their ease of operation, lower cost of treatment, and high treatment efficiencies. Several reactions

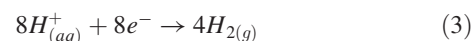
happen simultaneously during pollution removal in electrocoagulation systems. Concurrent oxidation and reduction happen on the anode and the cathode, respectively. Oxidation results in the generation of adsorbents like ferric or aluminum hydroxides, whereas reduction results in the evolution of hydrogen gas, which cause the adsorbent to float (Wang et al. 2009). Electrocoagulation is a widely used technique for the removal of pollutants in many industrial wastewaters. Electrocoagulation technique has been used as a post-biological treatment process for treatment of leachate (Dastyar et al. 2015; Fernandes et al. 2017), POME (Bashir et al. 2016; Nasution et al. 2014; Phalakornkule et al. 2010), oily wastewater (Chavalparit and Ongwandee 2009; Hassan et al. 2015), dye wastewater (Assémian et al. 2018), and restaurant wastewater (Qin et al. 2013).

Electrocoagulation technology is based on the principles of charge neutralization, adsorption, and precipitation by the electrochemical generation of destabilizing agents that remove various pollutants in water (Ilhan et al. 2008; Thakur and Mondal 2016). Reactions occurring at the anode and the cathode are as follows:

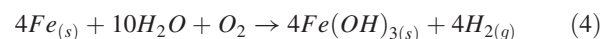
At Anode



At Cathode



Overall



Monopolar mode electrocoagulation, where all the electrodes connected to a DC power supply, is the most studied electrocoagulation system in recent times. Monopolar mode electrocoagulation systems, reported in the literature, have retention times greater

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than 30 min, with higher current densities. In a monopolar mode electrocoagulation system, applied to synthetic wastewater, the chemical oxygen demand (COD) removal efficiency was observed to be 69.23% when the retention time was kept at 58.86 min and the current density of 50.97 A/m² (Sandhwar and Prasad 2017). A monopolar mode electrocoagulation system, applied to tannery wastewater, had shown a COD removal efficiency of 81% at 6-h retention time when the current density was 400 A/m² (Elabbas et al. 2016). In monopolar mode systems, all the electrodes are connected to a power supply unit. This configuration results in higher electricity consumption. Moreover, monopolar electrocoagulation systems occupy a larger footprint when applied in field scale. The limitations of the monopolar mode electrocoagulation system can be addressed with the bipolar-mode electrocoagulation system, which consists of sacrificial electrodes, placed in between two electrically connected end-electrodes. The sacrificial electrodes are not connected to the electrical power supply. The neutral plates are transformed into charged plates with opposite charges on the two sides when an electrical current is passed through the system. This mode of electrode arrangement increases the surface area for the reaction (by increasing the number of electrodes) without any additional electrical connection (Mollah et al. 2004). This increases the pollutant removal efficiency and reduces the power consumption and space requirement.

In this study, a continuous bipolar mode electrocoagulation (CBME) system has been developed at laboratory-scale for polishing an anaerobically-treated POME. The aim of this study was to develop a design for the CBME system that can achieve high treatment efficiency, reduce the operating cost, and simplify the operation. Optimization was done for the process variables such as; initial pH; retention time; reaction area; and current density for achieving high removal of residual organics, measured as total organic carbon (TOC), and total phosphorus (TP). Optimization study has been carried out using a statistical technique called response surface methodology (RSM). Full quadratic models were developed for predicting the pollutant removal efficiencies. The micropollutant analysis was carried out to identify the organic compounds present in the POME before and after treatment at the optimized condition.

Materials and Methods

Sampling of the Wastewater

An anaerobically treated POME was used in this study. The wastewater was sampled at the outlet of a wastewater treatment plant (WWTP) of a palm oil mill industry located in Andhra Pradesh, India. The WWTP has adopted an anaerobic process for treating wastewater. The wastewater was collected from a storage tank that was placed after the anaerobic reactor and preserved at 4°C until use. Prior to the laboratory test, the collected wastewater was uniformly mixed, and initial characterization was carried out.

Experimental Set-Up and Procedure

A 1-L (effective volume: 765 mL) CBME setup was fabricated using a polyacrylic sheet. Iron electrodes (99% purity), each having a dimension 15 × 3.4 × 0.3 cm, were inserted with a clear spacing. The number of electrodes was varied between 4 and 15. The number of electrodes varies the surface or the reaction area in the system. The two end electrodes were connected to a power supply. The remaining electrodes were used as sacrificial electrodes. A power supply pack was used, which had an input voltage of 250 V and a variable output of 0–220 V. Fig. 1(a) represents the schematic, and Fig. 1(b) represents the photograph of the experimental set-up. The raw wastewater enters the reactor from the bottom. The treated wastewater leaves the reactor from the top. The electrodes were cleaned in a solution of HCl (35%) after each experiment in order to remove the passivation layer from the electrodes. The electrode surfaces were rinsed several times with deionized water before and after the experiment. All experiments were performed at 25°C.

The physicochemical characteristics of the inlet POME sample are shown in Table 1. The analysis was done in triplicate. The determination of pH, conductivity, TP, total dissolved solids (TDS), total suspended solids (TSS), sulfates, chlorides, calcium, magnesium, sodium, potassium, and COD were done following standard methods published in APHA/AWWA/WEF (2012). COD was measured using the closed reflux method. TOC and Total Nitrogen (TN) were characterized using a TOC analyzer (Shimadzu, TOC-L CPN, H54115000196AE, Hyderabad, India). The result indicates

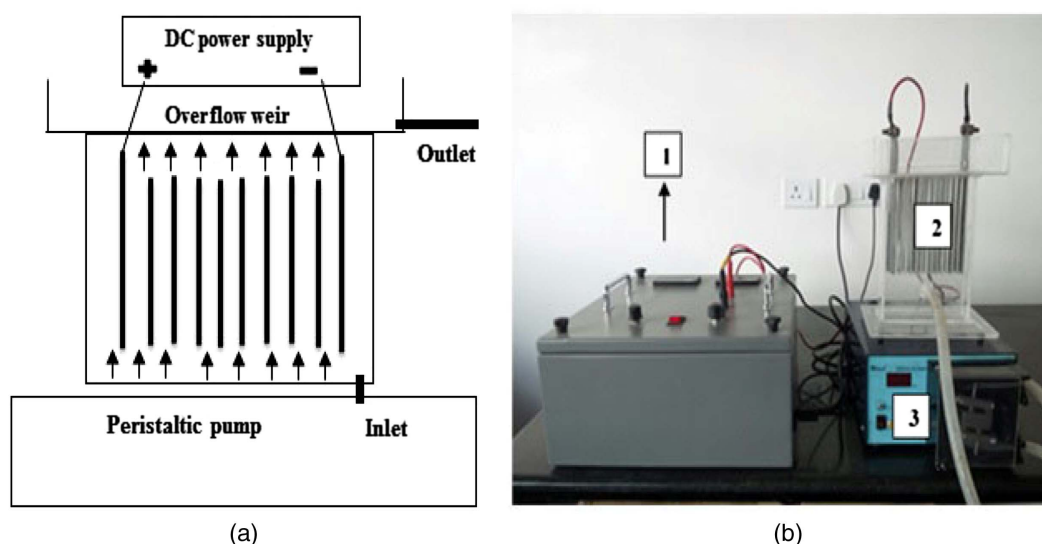


Fig. 1. CBME setup: (a) schematic; and (b) photograph. 1 = DC power supply; 2 = CBME chamber; and 3 = peristaltic pump.

Table 1. Initial characterization of the POME

Parameter	Unit	Value
pH	—	8.5 ± 1
Color	—	Dark brown
Electrical conductivity	mS/cm	16.9 ± 2.5
Total nitrogen	mg/L	76.37 ± 20
Total organic carbon	mg/L	2,550 ± 50
COD	mg/L	7,500 ± 20
TDS	mg/L	10,500 ± 10
TSS	mg/L	750 ± 5
Total phosphorous	mg/L	389 ± 9
Sulphate	mg/L	305 ± 15
Chloride	mg/L	2,708 ± 10
Calcium	mg/L	39.3 ± 5
Magnesium	mg/L	333.4 ± 15
Sodium	mg/L	67 ± 5
Potassium	mg/L	1,986 ± 5

that the inlet wastewater falls under the category of high-strength wastewater characterized by high COD (7,480–7,520 mg/L), TSS (745–755 mg/L), TOC (2,500–2,600 mg/L), and an intense brown color. The optimization process was carried out for maximizing the removal of TOC and TP. Micropollutant analysis was carried out using a high resolution mass spectrometer (HRMS). The HRMS (Agilent, 6545 LC-QToF, 1290 Infinity II, Santa Clara, California) was used for identification of both the known-unknowns and the unknown-unknowns. The instrument has a mass scanning accuracy of less than 0.8 ppm and the MS/MS mass accuracy of less than 2 ppm. The targeted screening approach was used for identification of the organic compounds in the wastewater samples. 20 μ L of the filtered sample was injected to the HRMS for analysis. The predominant masses present in the samples were identified by electrospray ionization (ESI) in both positive and negative modes. Molecular feature extraction (MFE), a data mining algorithm, was used to find the predominant masses present in samples. The targeted compounds were identified using a water screening library. The formula matching was carried out by the software, which considers mass accuracy, isotopic abundance, and isotopic spacing. Mass accuracy is maintained throughout the analysis after calibration with the help of an integrated calibrant delivery system. The liquid chromatogram (LC) and the HRMS method parameters are presented in Tables S1 and S2, respectively. The organic compounds with a score above 95% were selected and reported. The removal efficiency was calculated using Eq. (5)

$$\text{Removal Efficiency (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad (5)$$

where C_i and C_f = the initial and final concentrations of TOC and TP or abundance values in case of micropollutant analysis.

Energy consumption at the optimized condition was determined by Eq. (6)

$$\text{Energy Consumption (kW} \cdot \text{h/m}^3\text{)} = \frac{V \times A \times t}{Vol \times 1000} \quad (6)$$

where V = voltage; A = amperage applied; t = retention time in hours; and Vol = volume of effluent treated.

Experimental Design and Model Development

Central composite design (CCD), an experimental design under the domain of RSM, was used in this study. Minitab software (version 17) was used for creating the experimental design. Initial pH (pH),

Table 2. Independent variables and levels as per CCD

Variable	−2(α)	−1	0	+1	+2(α)
pH	3	4.7	6.5	8.2	10
Retention time (min)	0.5	2.8	5.2	7.6	10
Reaction area (cm ²)	204	344	484	625	765
Current density (A/m ²)	40	58.7	77.5	96.2	115

Table 3. Design matrix

Independent process variables (coded)				Responses (%)	
pH	RT	RA	CD	TOC removal	TP removal
−1	−1	−1	−1	57.62	36.25
1	−1	−1	−1	17.54	20.59
−1	1	−1	−1	64.80	18.10
1	1	−1	−1	51.91	20.59
−1	−1	1	−1	66.15	12.06
1	−1	1	−1	43.55	15.90
−1	1	1	−1	75.15	33.50
1	1	1	−1	72.23	39.83
−1	−1	−1	1	60.47	18.10
1	−1	−1	1	5.63	48.11
−1	1	−1	1	76.62	24.15
1	1	−1	1	22.38	54.99
−1	−1	1	1	58.43	6.83
1	−1	1	1	15.30	23.88
−1	1	1	1	64.71	41.23
1	1	1	1	24.99	45.01
−2	0	0	0	53.93	3.61
2	0	0	0	7.61	6.40
0	−2	0	0	7.30	19.27
0	2	0	0	47.45	47.80
0	0	−2	0	50.96	71.63
0	0	2	0	78.00	61.39
0	0	0	−2	70.77	40.92
0	0	0	2	62.45	56.27
0	0	0	0	52.20	78.00
0	0	0	0	48.30	75.20
0	0	0	0	58.17	76.75
0	0	0	0	55.45	71.63
0	0	0	0	60.20	70.50
0	0	0	0	53.50	71.63
0	0	0	0	58.70	73.62

retention time (RT), reaction area (RA), and current density (CD) were selected as independent process variables in the electrocoagulation process. Five levels were created for each factor in CCD to investigate the main effects and the interaction effects of the factors. Table 2 represents the various process variables and levels created for the design. Removal efficiencies of TOC and TP were chosen as responses (dependent variables). The experimental design resulted in 31 experimental runs. A full quadratic model, as shown in Eq. (7), was fitted to the experimentally obtained data points using multiple regression analysis. The equation describes the relationship between the independent and the dependent variables

$$Y = \beta_0 + \sum_{i=1}^j \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^{i < j} \sum_{j=1}^i \beta_{ij} X_i X_j \quad (7)$$

where X_i and X_j = the independent variables, influencing Y , the response variable; β_0 , β_i , β_{ii} , and β_{ij} = the i th linear, quadratic coefficient, and the ij th interaction coefficients, respectively. The model

analysis was performed with a Fisher's statistical test for analysis of variance (ANOVA). ANOVA was carried out by instantaneously solving equations for maximizing the removal of TOC and TP. The results were analyzed for the interactive effects of variables using response surface and contour plots. The RSM model predicts the response at the optimum operating conditions (Rout et al. 2016, 2017). Coefficient of determination and lack of fit values were used for validating the model. Verification experiments were carried out using optimal settings of variables for experimental validation of the models.

Results and Discussions

Statistical Analysis

Experimental runs were conducted in duplicates, based on the CCD design, for modeling the removal of TOC and TP. Table 3 represents the design matrix. Second-order polynomials were fitted with observed experimental responses. The results obtained from ANOVA are presented in Table S3 for TOC removal and in Table S4 for TP removal. The significance of each model term was verified by p-value. A p-value less than 0.05 confirms that the parameters

have a significant effect on treatment efficiency. The results depict that 11 out of 14 terms were found to be significant for TOC removal efficiency, which includes the linear terms - pH, RT, RA, and CD; quadratic terms - pH^2 , RT^2 , RA^2 , and CD^2 ; and interaction terms - $pH \cdot CD$, $RT \cdot CD$, and $RA \cdot CD$. The significant terms of independent process variables for TP removal efficiency were found to be the linear terms - pH, RT, and CD; quadratic terms - pH^2 , RT^2 , RA^2 , and CD^2 ; and interaction terms - $pH \cdot CD$, $RT \cdot RA$, and $RT \cdot CD$. Lack of fit test for TOC removal efficiency (p-value = 0.25) and TP removal efficiency (p-value = 0.20) was found to be nonsignificant. High R^2 values confirmed a good correlation between observed and predicted values. $R^2_{predicted}$ values represent the predictability of the model for new responses. Therefore, R^2 and $R^2_{predicted}$ values should be close enough to validate the model (Makwana and Ahammed 2017). Table 4 represents the model summary. R^2 , $R^2_{predicted}$, and R^2_{adj} are found to be in close agreement with each other proving the model to be significant. Plots of predicted versus observed values, shown in Fig. S1, prove that the quadratic model can be used for future predictability. After removal of nonsignificant terms, the modified quadratic model for TOC removal efficiency and TP removal efficiency were obtained as Eqs. (8) and (9) respectively.

Table 4. Model summary

Parameter	R^2 (%)	R^2 (adj) (%)	R^2 (pred) (%)	P_{lof} (lack of fit)	Model P
Total organic carbon	96.68	94.34	88.01	0.25	<0.0001
Total phosphorous	96.98	95.02	87.97	0.20	<0.0001

$$\begin{aligned}
 TOC\text{Removal}(\%) = & -250.8 + 39.98\ pH + 28.81\ RT \\
 & + 0.1575\ RA + 1.939\ CD - 2.045\ pH^2 \\
 & - 1.261\ RT^2 + 0.000123\ RA^2 \\
 & + 0.00768\ CD^2 - 0.2750\ pH \cdot CD \\
 & - 0.0860\ RT \cdot CD - 0.002325\ RA \cdot CD \quad (8)
 \end{aligned}$$

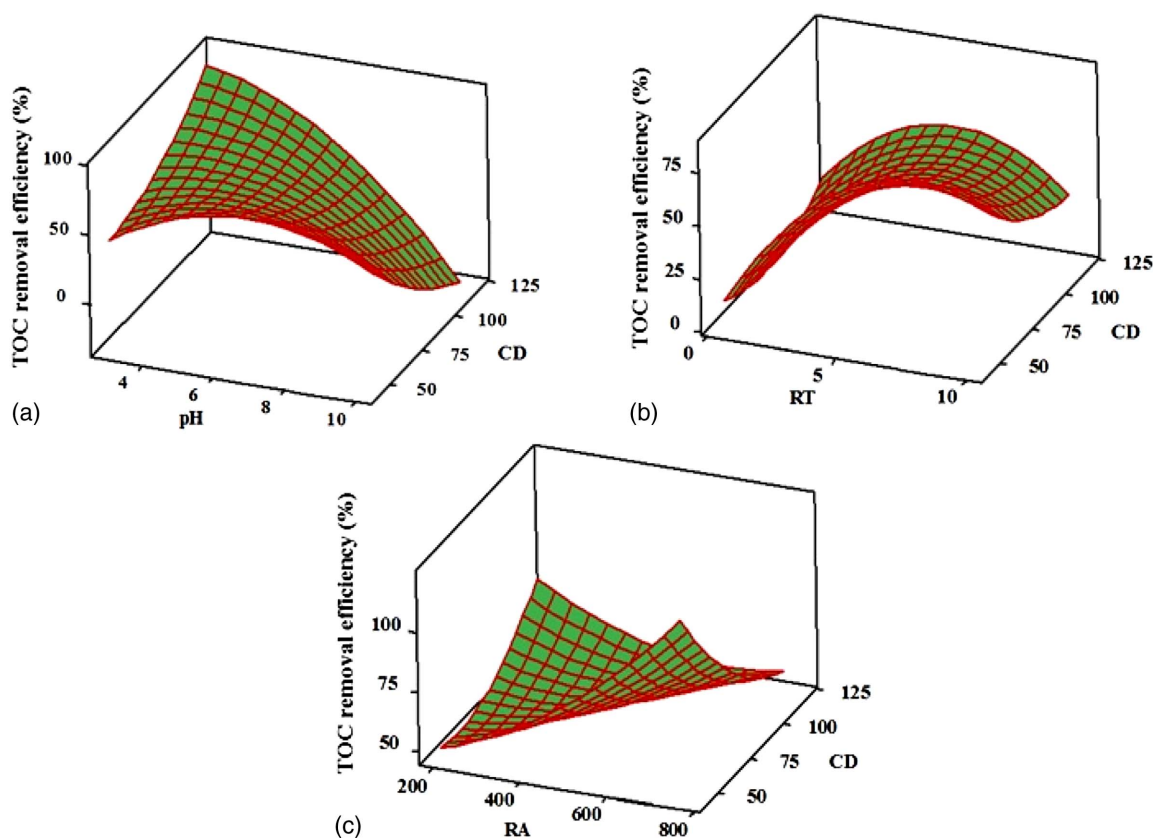


Fig. 2. Response surface plots for TOC removal: (a) pH and current density; (b) retention time and current density; and (c) reaction area and current density.

$$\begin{aligned}
TP\ Removal(\%) = & -303.6 + 82.36\ pH + 4.87\ RT \\
& + 0.0097\ RA + 1.694\ CD - 7.261\ pH^2 \\
& - 1.980\ RT^2 - 0.000149\ RA^2 \\
& - 0.02105\ CD^2 + 0.2080\ pH \cdot CD \\
& + 0.02451\ RT \cdot RA + 0.0923\ RT \cdot CD \quad (9)
\end{aligned}$$

TOC removal, a function of process variables is expressed using Eq. (8). Response functions such as linear, quadratic, and interactive have been included in the model equation explaining the correlation of each response variable with the process variables. Initial pH was found to be more significant among both first and second-order coefficients. Interaction coefficient term of initial pH and current density shows the highest degree of interaction. A positive value in main effect coefficients shows that TOC removal efficiency increased with an increase in the main effect. The negative sign in quadratic terms indicates the maximum level of response lies in the

selected range of variables. Positive signs in interaction terms indicate that both the process variables together show a synergistic effect, whereas, the negative term indicates that when one variable positively affects the response, the other interacting variable negatively affects the response (Shojaimehr et al. 2014). TP removal is shown by Eq. (9), which indicates that all the main effect and interaction effects are positive, and all the quadratic effects are negative. pH shows a more significant effect than other variables in main and quadratic terms. pH and current density interaction were found to be most significant among the interaction terms. Similar observations have been reported in the literature (Shojaimehr et al. 2014).

Significance of the Process Variables

The relationship between the independent process variables and the responses are explained by response surface and contour plots. Figs. 2–5 show the graphical representation of the effects of process variables on the removal efficiencies of responses. The relationships

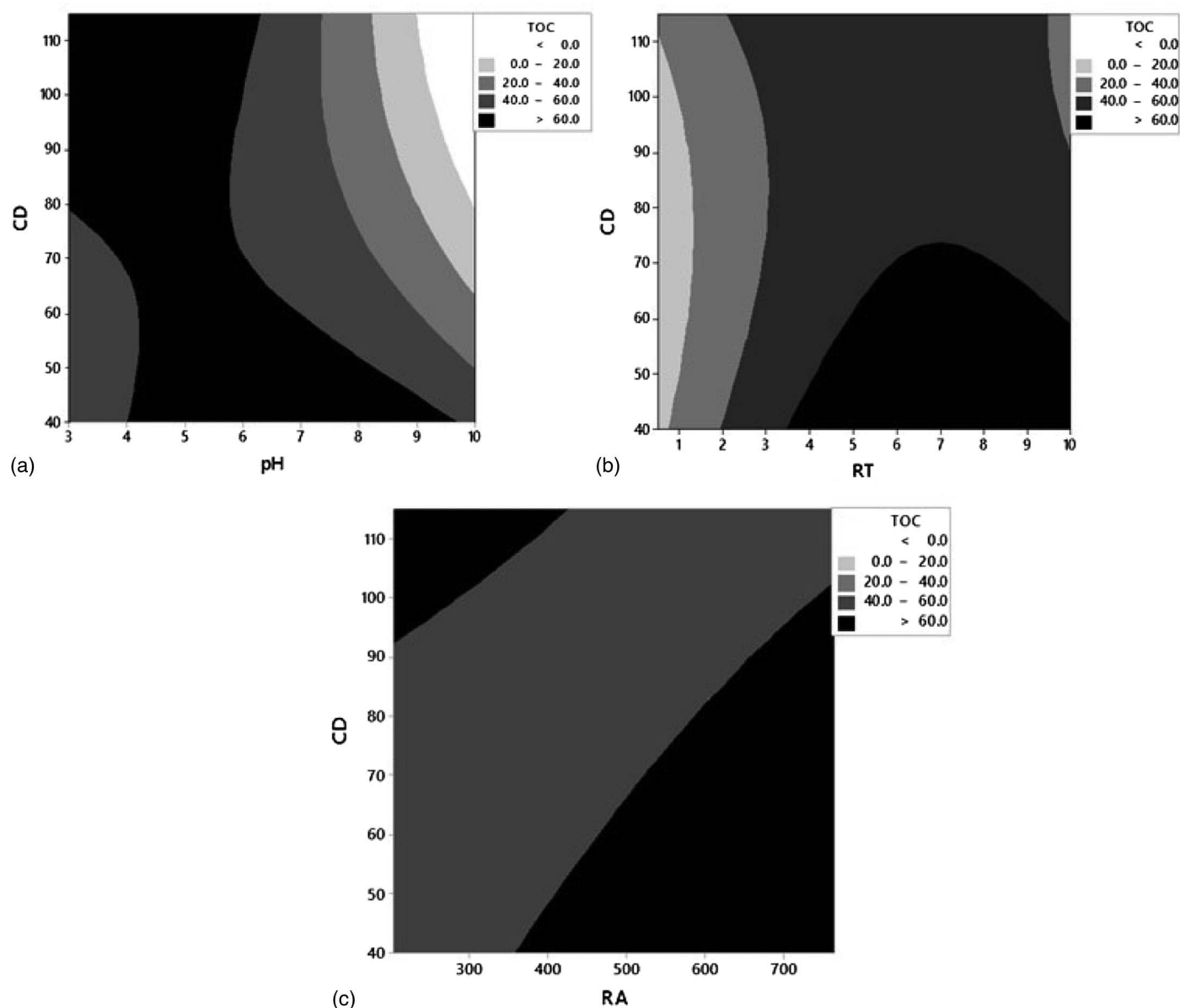


Fig. 3. Contour plots for TOC removal: (a) pH and current density; (b) retention time and current density; and (c) reaction area and current density.

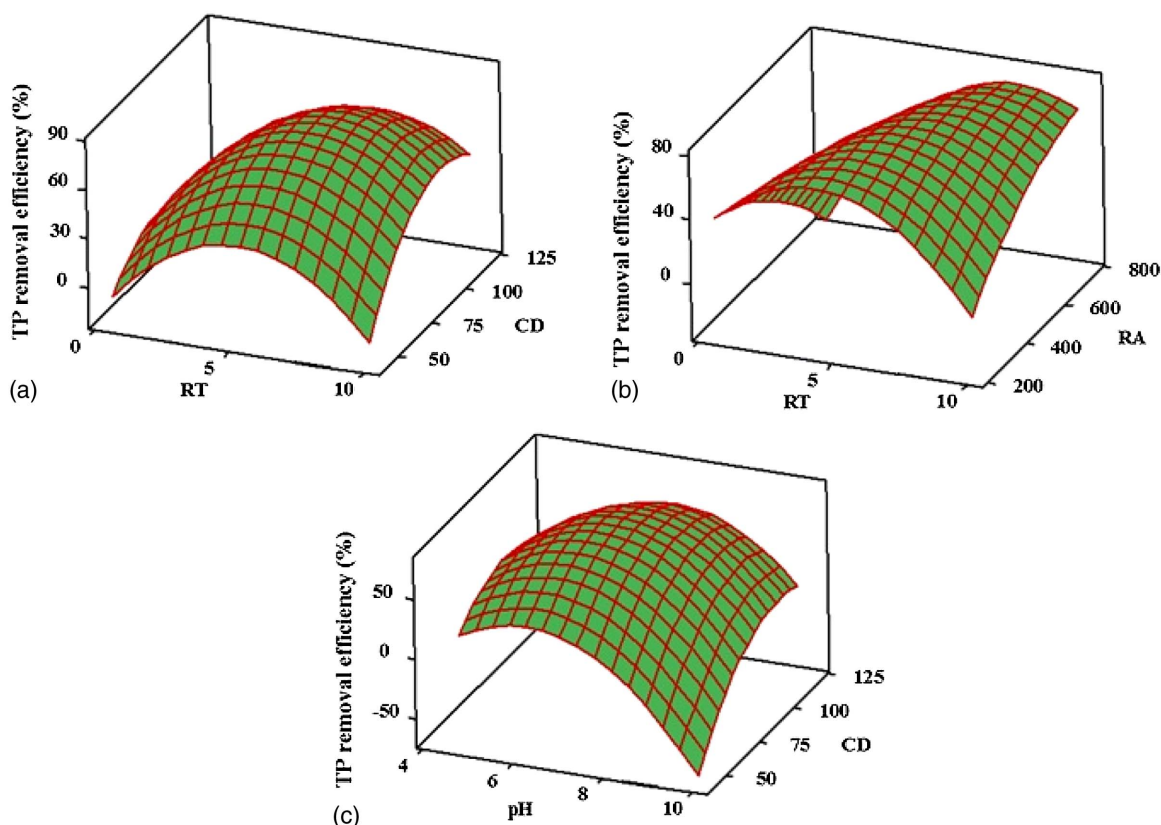
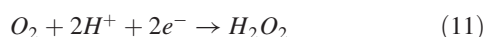


Fig. 4. Response surface plots for TP removal: (a) retention time and current density; (b) retention time and reaction area; and (c) pH and current density.

of the interaction terms with TOC removal efficiency are explained in Figs. 2 and 3. Figs. 2(a) and 3(a) depict higher removal efficiency (>60%) at higher current densities (>80 A/m²) and at pH range of 4–10; however, at higher pH and lower current densities, a similar effect was observed. A pH-dependent phenomenon was observed in the system. Variation in pH can change the surface charge of the particles, which, in turn, influences the removal of suspended organics from the effluent (Drogui et al. 2008). The mechanism of TOC removal occurs by indirect chemical oxidation or adsorption and charge neutralization. At pH 4–5.5, charge neutralization of particles usually happens (Wang et al. 2011) and at pH > 6.5, adsorption phenomenon is more evident (Damaraju et al. 2017) owing to the formation of Fe(OH)₃ flocs. Indirect chemical oxidation causes the organic compounds to undergo an oxidation process with the formation of intermediate compounds in the reactor. Indirect chemical oxidation can also occur when higher potentials are applied to the electrocoagulation process because of the oxygen evolution (Fernandes et al. 2017; Isarain-Chávez et al. 2014). Indirect chemical oxidation can occur at pH < 6. In this case, higher TOC removals occurred at a pH range of 4–6, when higher current densities applied, which might be the case of indirect chemical oxidation. Indirect chemical oxidation occurs by the following reactions represented in Eqs. (10) and (11)



Current density is an important factor in electrocoagulation where an increase in current density causes an increase in the production of metal species by the dissolution of anode following

Faraday's law. It can be ascertained from this case that at lower pH charge neutralization is favored as the higher amount of metal is dissolved due to the higher current density. At higher pH, adsorption is favored even at lower current densities. Retention time and current density plots are illustrated in Figs. 2(b) and 3(b). Higher TOC removal occurred at higher retention times (>4 min) and current density in the range of 40–70 A/m², later which, there is a reduction in removal efficiency. Higher retention time ensures more metal ions released at respective pH value. Reaction area and current density interactions are shown in Figs. 2(c) and 3(c). Reaction area plays a significant role in the CBME system as it provides more surface for reactions to happen and metal dissolution will be greater. About 60% removal efficiency was achieved with a reaction area greater than 350 cm² and a current density up to 99 A/m², as shown in contour plot Fig. 3(c). The interaction effects indicate that higher TOC removal is possible at lower current densities when higher retention time and reaction area are applied. This observation is different from the observations made with monopolar mode electrocoagulation systems where current density needs to be increased in order to increase the removal efficiency (Gengec et al. 2012; Ozay et al. 2018).

The relation between the interaction terms and TP removal efficiency are shown in Figs. 4 and 5. Retention time and current density interaction plots are shown in Figs. 4(a) and 5(a). The TP removal efficiency increased with an increase in retention time and current density up to a certain point. TP removal reduced beyond that point. Fig. 5(a) indicates that more than 70% removal efficiency can be achieved when the retention time is in the range of 4–8 min and the current density is in the range of 70–105 A/m². Higher phosphate removal at higher retention time and current

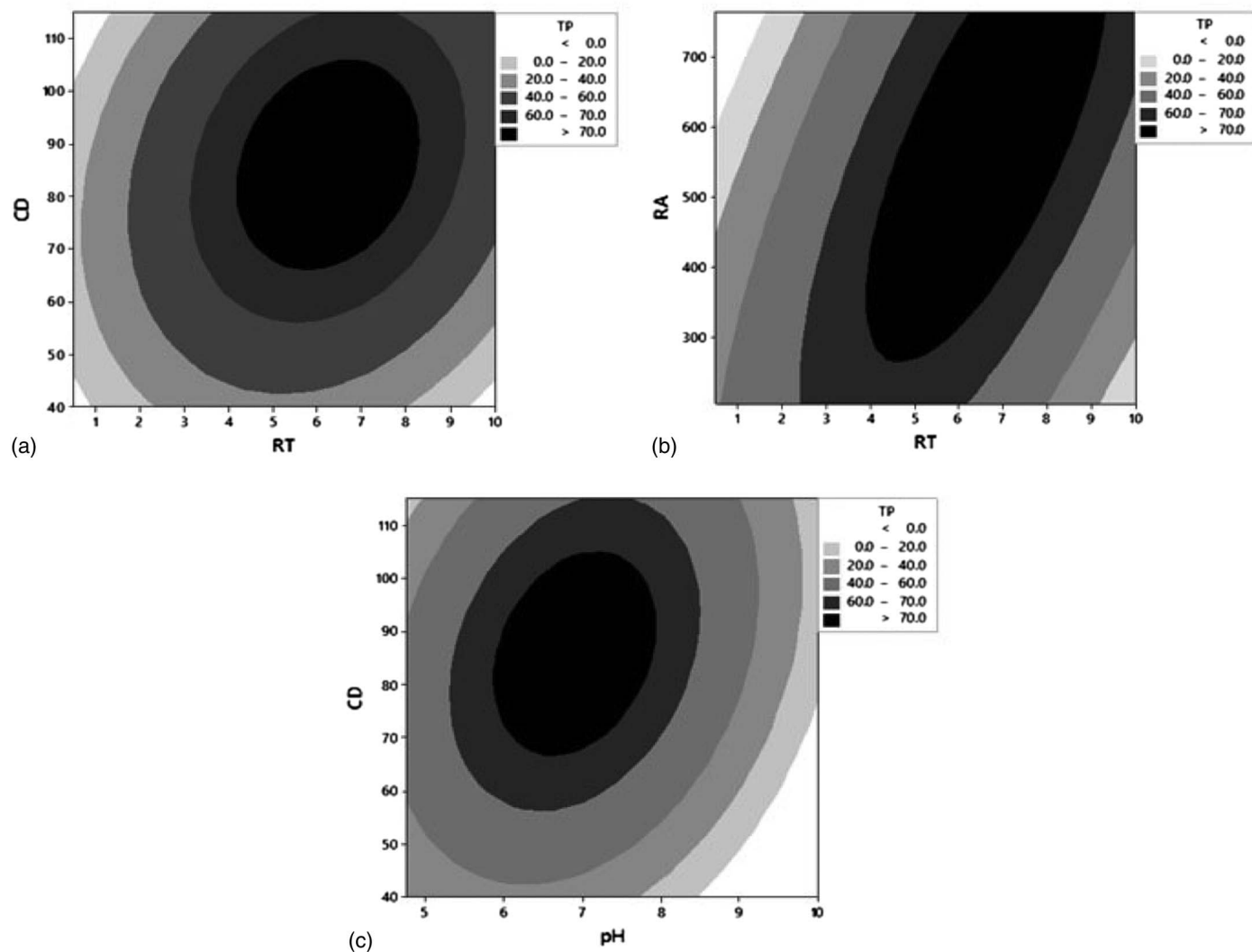


Fig. 5. Contour plots for TP removal: (a) retention time and current density; (b) retention time and reaction area; and (c) pH and current density.

densities can be attributed to the production of more adsorbents $[\text{Fe}(\text{OH})_3]$ (Vasudevan et al. 2009). Retention time and reaction area plots are depicted in Figs. 4(b) and 5(b). The higher TP removal is indicated at, the higher the reaction area and retention times. However, when the retention time is beyond 7 min, there is a reduction in TP removal. TP removal of more than 70% is possible at a retention time of 4–7 min and reaction area of 300–765 cm². Figs. 4(c) and 5(c) illustrate the pH and current density interaction plots. These plots indicate higher TP removal at a pH range (6–8) and current density (70–105 A/m²) where an increase or decrease to the range specified reduced the TP removal efficiency. Fig. 5(c) indicates removals above 70% at the pH and current density ranges specified. pH plays a significant role in phosphate removal. Phosphate precipitates as FePO_4 or gets adsorbed to the binding sites of $\text{Fe}(\text{OH})_3$ depending on pH range. Chemical precipitation in the electrocoagulation system can happen by the release of iron metal cations at the anodes. Chemical precipitation reactions are shown in Eqs. (12) and (13)



Ferric phosphates (FePO_4) tend to form at lower pH because of nonavailability of (OH^-) ions, which are needed to precipitate

Fe^{+3} as $\text{Fe}(\text{OH})_3$. At higher pH (above 7), $\text{Fe}(\text{OH})_3$ tends to be observed, which acts as an active binding site for adsorption (Sincero and Sincero 2003). However, precipitation can also occur to some extent at higher pH. In the present study, the TP removal was observed at pH 6–7.5, where both adsorption and precipitation is likely to occur. The interaction effects indicate that the higher TP removal in the CBME reactor is possible when near-neutral pH is applied at higher retention time and reaction area and at lower current densities.

Multiobjective Optimization

Multi-objective optimization was carried out for maximizing removals of TOC and TP. Optimization for multiple responses will be difficult, as the local optima are located in diverse regions. This problem of optimization is solved by selecting a desirability function. This function is based on developing a desirability function for each response, where the process variables for each response are transformed into a dimensionless desirability scale. The desirability scale ranges from 0 to 1, where 0 indicates undesirable response and 1 indicates a desirable response. The composite desirability function is the geometric average of individual desirability functions of responses (Bezerra et al. 2008). Fig. S2 illustrates the optimization plot, indicating a pH-of 6.4, a retention time of 7.69 min, a reaction

Table 5. Verification of experimental runs at optimum conditions

Optimum conditions	TOC removal efficiency (%)	TP removal efficiency (%)
Model response	79.9	74.6
Experimental results	77	73
Error	2.9	1.6
Standard deviation	±2.05	±0.8

area of 765 cm² and a current density of 77.8 A/m² to be the optimal point for maximum removal of TOC and TP. Individual desirability function for TOC and TP were found to be 0.99 and 0.90. Composite desirability was found to be 0.95, where all the values are close to 1, thereby, validating the optimal value. Conformational (experimental) runs were carried out with the optimized operating conditions predicted by the model. Table 5 indicates the predicted responses at optimal points along with the experimentally verified results. TOC removal was found to be 77%, and TP removal was 73%, thus showing a good correlation between observed and predicted responses at the optimized points. The ratio of the total surface area of the electrodes (*S*) to the volume of the CBME reactor (*V*) can be used as a parameter for upscaling the reactor from the laboratory to the field scale. At the optimized condition, the *S/V* ratio was found to be 76.5 m⁻¹. The *S/V* ratio obtained in this study is higher than other bipolar mode electrocoagulation reactors studied in the literature (Droguet et al. 2008; Golder et al. 2007; Wang et al. 2009) that provide more surface area for the reaction. The energy consumption at optimized conditions was calculated at 22.4 kW · h/m³. Table 6 compiles the literature on the application of the monopolar mode electrocoagulation system in different wastewater treatment. The retention time and current

densities considered for monopolar electrocoagulation were found to be higher than the CBME system described in this study. Energy consumption in the CBME system was found to be lower than the monopolar electrocoagulation systems. The corresponding energy cost will also be lower than the monopolar mode electrocoagulation system. The observations made in this study indicate that the CBME systems are improved and viable alternatives to monopolar systems. The design data generated in this study can be used to scale up the system.

Micropollutant Analysis

LC-HRMS analysis was carried out to screen the compounds in the inlet and treated samples, and their removal efficiencies. The percentage of removal was calculated based on the abundance (corresponds to the area under the curve) values of the micropollutants in the inlet and outlet samples. POME is a plant-based effluent which may contain phenolic compounds, amino acids, flavonoids, and bioactive compounds (Siddhu and Saxena 2017). Fig. S3 represents the extracted ion chromatograms of ESI positive and ESI negative of the inlet and outlet samples of POME. The majority of peaks identified in inlet samples were found to be downregulated or disappeared in outlet samples indicating the removal of organic compounds. Table 7 indicates the organic compounds (overall score of identification above 95% for matching compounds) identified in the inlet and outlet samples, and their removal efficiencies. The samples contained phenolic compounds, amino acids, xenobiotics, and pesticides. The organic compounds removal was found to be 100% in most of the cases. Fig. 6 represents the physical appearance of samples before and after CBME treatment. A significant decrease in color intensity was found after the treatment, indicating the removal of color-causing compounds.

Table 6. Literature review on monopolar mode electrocoagulation system

Wastewater type	Electrode configuration	Optimum operating conditions	Pollutant removal efficiency	Energy consumption (kW · h/m ³)	Reference
Synthetic wastewater	Monopolar	pH-10; Volts-17 V; RT-68 min	Nitrate-87.95%	144	Emamjomeh et al. (2017)
POME	Monopolar	pH-4.5; RT-65 min; CD-56 mA/cm ²	COD-75.4%	39	Bashir et al. (2016)
Acid mine water	Monopolar	CD-25 mA/cm ² ; RT-240 min	Sulphate-63.8%	140	Nariyan et al. (2018)
Cereal products wastewater	Monopolar	pH-5.53; RT-90 min; CD-50 A/m ²	COD-22.8%	52	Droguet et al. (2008)
Shale gas wastewater	Monopolar	RT-60 min; pH-7.9	TOC removal-50% for actual shale gas wastewater	60	Kausley et al. (2017)
POME	CBME reactor	pH-6.44; RT-7.69 min; RA-765 cm ² ; CD-77.8 A/m ²	TOC removal-77%; TP removal-73%	22.4	Present study

Table 7. Micropollutant analysis

Formula	Name	Type of compound	POME inlet abundance	POME outlet abundance	Percentage removal
ESI positive					
C ₁₀ H ₁₀ Cl ₂ O ₃	2,4-DB/2,4-Dichlorophenoxybutyric acid	Phenolic compound	278,767.4	64,516.38	76.85
C ₁₂ H ₁₈ O	n-Hexylphenol	Phenolic compound	106,717.4	0.001	100
C ₉ H ₁₁ NO ₄	Levodopa	Amino acid	36,909.05	0.001	100
ESI negative					
C ₉ H ₁₁ NO ₃	Tyrosine	Amino acid	103,828	0.001	100
C ₇ H ₅ NS	Benzothiazole	Plant metabolite, Xenobiotic	86,417.21	0.001	100
C ₁₄ H ₂₁ NO ₄	Diethofencarb	Pesticide	54,898.64	0.001	100
C ₁₀ H ₉ N	Quinaldine	Bioactive compound	43,015.48	0.001	100

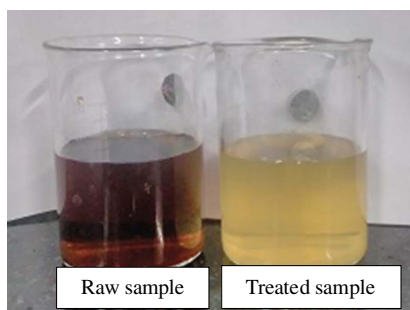


Fig. 6. Physical appearance of POME before and after CBME treatment.

Conclusions

The current research was a study on the application of the CBME system for downstream processing of biologically treated POME for maximizing the removal of TOC and TP. The results depicted the highest TOC and TP removals of 77% and 73%, respectively, at the optimized operating parameter of pH 6.4, retention time 7.69 min, reaction area 765 cm², and current density 77.8 A/m². At optimized conditions, the surface area to volume ratio was found to be 76.5 m⁻¹, and energy consumption was found to be 22.4 kW · h/m³. Retention time, *S/V* ratio, and current density are the important parameters that can be used for scaling up the reactor. The CBME reactor operates at a retention time of less than 10 min with a continuous operation, which can save a lot of space in industries when compared to monopolar electrocoagulation systems. Reaction area can be increased in the CBME system without any additional electrical connections, which provide the operational flexibility for enhancing the treatment efficiency. The CBME system was efficient in the removal of color and organic compounds like xenobiotics, phenolic compounds, bioactive compounds, and pesticides. Electrode passivation could be a limitation of CBME system that can be reduced by regular cleaning of electrodes.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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Supplemental Data

Figs. S1–S3 and Tables S1–S4 are available online in the ASCE Library (www.ascelibrary.org).

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