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Evaluating the efficiency of combined electrocoagulation and electrooxidation in industrial effluent treatment

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ABSTRACT

This study aimed to evaluate the effectiveness of hybrid electrocoagulation (EC) and electrooxidation (EO) processes in treating effluent water from the industrial process plant in Owerri. The research involved assessing the physicochemical properties of the wastewater against the discharge standards set by the National Environmental Standards and Regulations Enforcement Agency. The treatment process used iron electrodes for both EC and EO, with optimal treatment times determined as 20 minutes for EC and 30 minutes for EO. Current densities ranging from 4.75 to 12.36 mA/cm² were tested. Key findings indicated that through EC, lead was completely removed, and copper and nickel concentrations were significantly reduced. EO further decreased turbidity and total dissolved solids (TDS) levels. The hybrid EC-EO process achieved a reduction in turbidity to acceptable discharge limits and significantly lowered TDS levels. However, a notable increase in chemical oxygen demand was observed during the hybrid treatment (up to 1099.87%), potentially due to operational issues such as electrode deposition and inadequate mixing. The limitations of the study included operational challenges such as equipment malfunction and human error, which affected the consistency of results. Future research should aim at optimizing process parameters, exploring alternative electrode materials, and addressing operational challenges to improve the efficiency and consistency of the EC-EO hybrid treatment method.

Keywords: electrocoagulation, electrooxidation, wastewater treatment, effluent water, heavy metals, process optimization

INTRODUCTION

Water pollution has become a critical environmental issue, affecting ecosystems, human health, and sustainable development. Industrial activities are a major contributor to this pollution, with wastewater from these processes introducing a variety of pollutants into natural water bodies (Yang et al., 2022). As industries continue to expand, the volume and complexity of wastewater generated also increase. This poses significant environmental challenges (Onu et al., 2023; Singh et al., 2023). In Owerri, the Nigerian Bottling Company (NBC) operates a process plant that produces large quantities of effluent water. This wastewater contains a mix of organic and inorganic contaminants, including suspended solids, dyes, chemicals, and potentially harmful microorganisms. Effective treatment of this effluent is important to mitigate its environmental impact and ensure compliance with regulatory standards (Silva, 2023).

Regulatory agencies like National Environmental Standards and Regulations Enforcement Agency (NESREA) in Nigeria have established discharge standards to ensure that industrial effluents do not endanger the ecosystem

(Okechukwu, 2024). Industrial wastewater from processes such as electroplating, oil refining, textiles, dairy production, distillation, and automotive manufacturing contains harmful substances like organic and inorganic pollutants, heavy metals, colorants, suspended solids, oil, grease, biological oxygen demand (BOD), and chemical oxygen demand (COD) (Demirci et al., 2015). This heightened awareness has sparked interest in developing more efficient and environmentally friendly wastewater treatment technologies to minimize negative impacts on aquatic ecosystems and the environment as a whole. Advanced oxidation processes (AOPs) and electrocoagulation (EC) are among the methods being explored for treating various types of industrial wastewater (Oturan & Aaron, 2014).

The high cost of conventional wastewater treatment methods and their various constraints in wastewater treatment have been a concern for many stakeholders. The major conventional methods for the treatment of wastewater include biological processes (Nowak et al., 2019), membrane processes, adsorption processes (Sessarego et al., 2019), AOPs (Brink et al., 2018), coagulation/flocculation processes, and ion exchange processes. Most conventional methods require high personnel training, high capital and operational costs, and produce a high amount of sludge and secondary pollutants (Ezechi et al., 2020). While the volume of industrial and domestic waste in many countries and regions has been increasing, waste management techniques such as landfills and wastewater treatment facilities are overburdened (Ezechi et al., 2020). These constraints have led to the development of an environmentally friendly approach that is cheap and shows consistent pollutant removal capacity.

EC and electrooxidation (EO) are promising electrochemical methods that offer several advantages over conventional treatment processes (Biswas & Goel, 2022). EC involves the in-situ generation of coagulants by electrolytic oxidation of sacrificial anodes, typically made of iron or aluminum. This process effectively destabilizes, and aggregates suspended particles and colloids, facilitating their removal from the wastewater. The added benefit of EC is its ability to simultaneously remove a variety of pollutants, including heavy metals and organic compounds, through mechanisms such as adsorption and precipitation (El-Ashtoukhy et al., 2020). EO, on the other hand, utilizes anodic oxidation to generate reactive species like hydroxyl radicals, which can degrade a wide range of organic pollutants. This process can achieve high levels of mineralization, converting complex organic molecules into carbon dioxide and water, thus reducing the BOD and COD of the treated effluent (Bhandari & Ranade, 2014). Combining EC and EO can synergistically enhance the treatment efficiency, addressing both particulate and dissolved contaminants effectively (Asfaha et al., 2021).

Given the growing environmental concerns and stringent discharge regulations, implementing advanced treatment technologies like EC and EO can provide a sustainable solution. The successful application of these technologies will not only improve the quality of discharged effluent but also contribute to water conservation efforts by enabling the reuse of treated water within the plant. This project aims to explore the effectiveness of the combined use of EC and EO as an advanced treatment solution. This will provide valuable insights into the practical challenges and operational considerations associated with electrochemical treatment methods, contributing to the broader field of environmental engineering and sustainable water management and establishing replicability in other industries in Nigeria.

METHODOLOGY

Various instruments and materials were used for the EC and EO processes. Key equipment included a HI2209 pH meter (HIANNA Instruments), a TTi EL302R DC power supply, a La Motte Colorimeter Smart 3 model, and a PALINTEST PC 300 Meter. Additionally, a BriSunshine Lab Turbidity meter, an atomic absorption spectrophotometer VGP 210 model (Bulk Scientific), a titration setup, an XL830L portable digital multimeter, and cuvette cells were employed. Standard glassware such as measuring cylinders, Erlenmeyer flasks, conical flasks, and beakers were also utilized. The primary raw materials were aluminum and iron electrodes, filter papers, funnels, CuSO4, PbSO4, and distilled water. Iron and aluminum were selected as electrode materials for the EC and EO processes due to their effectiveness in facilitating the removal of heavy metals and other contaminants from wastewater. Iron, in particular is known for its ability to generate ferrous ions when oxidized, which can effectively coagulate suspended particles and heavy metals (Pal, 2017). Aluminum is also commonly used in EC due to its high reactivity and ability to form aluminum hydroxide, which aids in the removal of contaminants (Hasnaoui et al., 2024).

Sample Collection and Characterization

A 50-litre wastewater sample was collected from the NBC's process plant in Owerri. The wastewater sample was analyzed for turbidity, conductivity, pH, total dissolved solids (TDS), BOD5, COD, heavy metals (Zn, Ni, Pb, and Cu), dissolved oxygen, and sulfates using standard procedures. The PALINTEST PC 300 Meter was used to assess the conductivity. Here, the probe was rinsed with distilled water, set to conductivity mode, and immersed in the sample until stabilization. Similar to conductivity testing, the pH was measured by setting the PALINTEST PC 300 Meter to pH mode and immersing the probe in the sample. TDS was determined using the PALINTEST PC 300 Meter set to TDS mode, following the same procedure as for pH and conductivity. The turbidity meter was stabilized for 15 minutes, calibrated with distilled water to 0.00 NTU, and then set to 200 NTU, and the sample reading was multiplied by 200 NTU for the final value.

The sample was split into two parts: one was tested immediately for dissolved oxygen, and the other was incubated in the dark at 20 °C for five days. BOD was calculated as the oxygen difference between the two tests in mg/L. A dissolved oxygen meter and sensor measured the dissolved oxygen by inserting the probe into the sample and allowing the temperature to stabilize before recording. COD was measured using the Colorimeter Smart 3 model, and heavy metals were analyzed using atomic absorption spectroscopy (AAS) with an AAS model 210VP. The metals analyzed included zinc, copper, lead, and nickel.

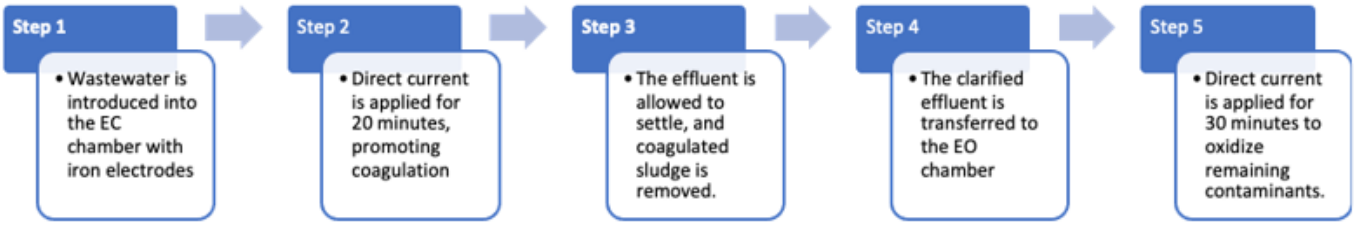

Figure 1. Summary process flow of the combined EC-EO process (Source: Authors' own elaboration)

Determination of Optimum Time for Electrocoagulation and Electrooxidation

The optimal time was determined at 0.09A and 15V. The wastewater sample was allowed to undergo EC at intervals of 10 minutes from 0 to 90 minutes (10, 20, 30, 40, 50, 60, 70, 80, and 90). After each run, samples were collected and tested. Conductivity was used as the parameter to determine the optimal time for EC. The time where the parameter was lowest was chosen as the optimal time. The optimum time was recorded at the lowest conductivity, which was 20 minutes.

TDS was used as the parameter to determine the optimal time for EO. The optimal time was determined at 0.09A and 15V also. The wastewater sample was allowed to undergo EO at intervals of 10 minutes from 0 to 90 minutes (10, 20, 30, 40, 50, 60, 70, 80, and 90). The time where the parameter TDS was lowest was chosen as the optimal time. The optimum time was 30 minutes.

Determination of Current Density for Electrocoagulation and Electrooxidation

Current density is given as the current supplied divided by the total surface area of the electrode. To determine the current density for EC, the surface area of the aluminum electrode was measured. The current was regulated using the TTi EL302R DC power supply. At a specific current, the current density was obtained by dividing by the total surface area of the aluminum electrode.

To determine the current density for EO, the current density in EO changed from what it was in EC by measuring the surface area of the iron electrode and then dividing the current supplied by the surface area determined. The current was regulated using the TTi EL302R DC power supply.

Electrocoagulation

The electrolytic setup was a 1,200 ml Pyrex plastic beaker containing 1,000 ml of effluent water from NBC and a pair of aluminum electrodes for EC spaced 8 cm apart and connected to a TTi EL302R DC Power, supplying varying currents from 100 mA, 120 mA, 140 mA, and 160 mA to 260 mA. The electrodes were submerged into the beaker containing the wastewater. Proper care was taken to ensure that the electrodes did not come in contact with the walls of the plastic beaker. The power was then turned on. After setting the readings of the power supply to the desired current, the stopwatch was started. After the process, the collected samples were filtered and tested. The optimal time of the experiment was determined to be 20 minutes (the time when the conductivity was lowest).

To monitor the effect of varying current density, the wastewater sample was allowed to undergo EC at the optimal time of 20 minutes, and the corresponding voltage after varying the currents from 100 mA, 120 mA, 140 mA, 160 mA, 180 mA, 200 mA, 220 mA, and 240 mA to 260 mA. The surface area of the electrodes and the distance between them were kept constant throughout the experiment. Samples of the electro coagulated wastewater were collected in labelled bottles for each current density and tested in the lab for COD, TDS, turbidity, and heavy metals such as lead, nickel, and copper.

Electrooxidation

The EO setup was similar to the EC process. Iron electrodes were used instead. The optimal time of the experiment was determined by turning on the power supply and allowing the sample to undergo EO at intervals of 10 minutes from 0 to 90 minutes. After each 10-minute interval, the sample was collected in a bottle and labelled. Each sample was tested in the lab for TDS, and the optimal time was taken as the time at which TDS was the lowest (30 minutes). The current density was determined by dividing the varying currents supplied by the total surface area of the iron electrode in contrast with EC.

The Combined EC-EO Process

The hybrid EC and EO process was designed to leverage the strengths of both methods in treating effluent water from the industrial process plant (**Figure 1**). The experimental setup involved a sequential application of EC followed by EO.

Electrocoagulation phase

The process started with EC Phase, where iron electrodes were submerged in the wastewater. To check the effect of the hybrid EC and EO process, the voltage was used at 20V with a corresponding current at 0.24A for EC. A direct current was applied, generating coagulants from the anode, which facilitated the aggregation of suspended particles and contaminants, including heavy metals. The optimal treatment time for this phase was determined to be 20 minutes. After the EC phase, the treated effluent was allowed to settle for a brief period to facilitate the separation of coagulated sludge.

Electrooxidation phase

Following the separation, the clarified effluent was subjected to EO. In this phase, the same iron electrodes were used, and a direct current was again applied. The EO process aimed to further degrade organic pollutants and reduce turbidity and TDS levels. The optimal treatment time for the EO phase was established at 30 minutes, during which the current density was adjusted to enhance the oxidation of remaining contaminants.

Table 1. Experimental results of the physicochemical properties of the wastewater samples

Parameters	NESREA discharge standards	Measured values of wastewater
pH	6-9	6.40
Turbidity (NTU)	5.0	200
Conductivity (µS/cm)	2,000	1,500
TDS (mg/l)	500	975
BOD (mg/l)	50	8.0
COD (mg/l)	90	344
Dissolved oxygen (mg/l)	> 7.50	9.50
Zinc (mg/l)	2.00	1.91
Copper (mg/l)	0.50	2.035
Lead (mg/l)	0.05	1.625
Nickel (mg/l)	0.05	1.02
Sulphate	250	39.47

AAS Method

AAS is used in food, beverage, water, chemical research, and pharmaceutical analysis. The sample was filtered through a filter paper. The AAS was set to measure the absorption from the hollow cathode lamp of any of the metals. The instrument was put into use, using an acetylene/air flame adjusted to the blue zone of the flame. The appropriate wavelength of each element that corresponded to the cathode lamp was selected. So, to start; the known standards in concentration are passed through the AAS, and the absorbance values are obtained. A graph of absorbance vs. concentration is plotted (a line of best fit is drawn). Then, the unknown samples are now passed through the AAS. The absorbances are recorded. From the graph, the absorbances of the unknown samples will then be used to get the required specific concentrations.

Colorimeter

First of all, we tested for standard concentrations: For copper solutions: 25 ml of $CuSO_4$ + 25 ml of distilled water to make a total of 50 ml of $CuSO_4$ solution. Then, at each volumetric flask, 2, 4, 6, 8, and 10 ml were pipetted into the flask and made to add up to 25 ml of distilled water (these were the standard solutions). For $PbSO_4$ solutions: 25 ml of $PbSO_4$ + 25 ml of distilled water to make a total of 50 ml of $PbSO_4$ solution. Then, at each volumetric flask, 2. 4, 6, 8, and 10 ml were pipetted into the flask and made to add up to 25 ml of distilled water (these were the standard solutions). The standards were first used to calibrate the equipment. Then, the apparatus was used to check for all the parameters to be found. For the turbidity, results were obtained in formazin attenuation unit (FAU) and then converted to nephelometric turbidity unit (NTU), where 1 FAU = 1 NTU.

Analysis of Results Data

Using MS Excel statistical analysis, the data obtained from the experiments were analyzed and presented in line graphs and bar charts for easy interpretation.

RESULTS AND DISCUSSION

The use of EC and EO in treating effluent water from the NBC process plant demonstrates considerable potential in mitigating wastewater pollution.

Table 2. Optimum time for EC and EO

Time (min)	EC (conductivity [µS/cm])	EO (TDS [mg/l])
10	1,000.5	725.15
20	875.7	715.21
30	880.4	700.62
40	1,200.9	885.75
50	1,300.7	899.89
60	1,115.0	860.26
70	895.6	865.13
80	900.5	850.12
90	890.1	821.14

A comparison of the measured physicochemical properties of the discharge water from the effluent treatment plant (ETP) against the discharge standards set by the NESREA reveals significant discrepancies, as shown in **Table 1**. The wastewater sample exceeded NESREA limits for multiple parameters, including turbidity, conductivity, TDS, BOD, COD, copper, lead, nickel, and sulphate, while meeting the standards only for dissolved oxygen and zinc. These findings indicate that the wastewater is highly polluted and must be treated before being discharged into the environment.

The turbidity of the wastewater, measured at 200 NTU, significantly surpassed the NESREA limit of 5.0 NTU, indicating a high level of suspended particles. Conductivity was slightly below the limit, suggesting moderate ionic content, but TDS levels were nearly double the acceptable threshold, further indicating substantial dissolved substances. The BOD and COD values of 8.0 mg/L and 344 mg/L, respectively, far exceeded the permissible limits, reflecting substantial organic matter and chemical pollutants within the water. Heavy metal concentrations presented severe deviations from regulatory standards, with copper, lead, and nickel levels recorded at 2.035 mg/L, 1.625 mg/L, and 1.02 mg/L, respectively, greatly surpassing the NESREA thresholds. These results are similar to those found in other industrial wastewater studies, such as a study by Ahmad et al. (2018), who found similar violations of discharge standards in industrial wastewater. EC, EO, and a combination of the two were employed to treat the wastewater to ensure that the latter parameters were within the discharge standards.

Process Optimization

Process time optimization is a critical factor in achieving maximum contaminants removal in electrochemical wastewater treatment processes. The results, shown in **Table 2**, indicate that the optimal treatment time for EC is 20 minutes, achieving the lowest conductivity value of 875.7 µS/cm. For EO, the optimal time was determined to be 30 minutes, corresponding to the maximum reduction in TDS to 700 mg/L.

These findings demonstrate the efficiency of both EC and EO at their respective optimal times. During EC, the initial decrease in conductivity from 1,000.5 µS/cm at 10 minutes to 875.7 µS/cm at 20 minutes suggests a significant removal of ionic species. Beyond 20 minutes, conductivity values increased, indicating a possible re-release or incomplete removal of contaminants, likely due to electrode passivation or saturation of the coagulation process. Research by Gasmi et al. (2022) indicates that after a certain point in the coagulation

Table 3. Current density of aluminum and iron (electrode surface area of aluminum and iron are 25 cm^2 and 21.04 cm^2, respectively)

Current (mA)	Current density of aluminum (mA/cm^2)	Current density of iron (mA/cm^2)
100	4.00	4.75
120	4.80	5.70
140	5.60	6.65
160	6.40	7.60
180	7.20	8.56
200	8.00	9.51
220	8.80	10.46
240	9.60	11.41
260	10.40	12.36

process, the system may reach a saturation point where the coagulant's effectiveness diminishes. This saturation can lead to the re-dispersion of previously removed particles back into the solution, contributing to an increase in conductivity.

In the case of EO, the reduction of TDS from 725.15 mg/L at 10 minutes to 700.62 mg/L at 30 minutes highlights the process's effectiveness in degrading dissolved organic and inorganic substances. Extending the treatment beyond 30 minutes resulted in increased TDS levels, suggesting diminished returns in contaminant removal efficiency, potentially due to secondary reactions or breakdown of intermediates into more stable, non-removable forms. At the optimized times of 20 minutes for EC and 30 minutes for EO, the hybrid process was monitored for its efficacy in reducing these pollutants, corroborating with Jones et al. (2021).

Current Density Analysis

To establish a suitable operational range for the EC and EO processes, a systematic evaluation of current and current density was undertaken.

The DC power supply gave out a maximum voltage of 33V, so the choice of currents to be varied was chosen in a way that does not exceed the corresponding maximum output of voltage.

Table 3 presents the varying currents and their corresponding current densities for aluminum and iron electrodes, calculated by dividing the currents (ranging from 100 mA to 260 mA) by the surface area of the electrodes (25 cm^2 for aluminum and 21.04 cm^2 for iron) used in EC and EO processes. The calculated current densities for aluminum electrodes ranged from 4.00 mA/cm^2 to 10.40 mA/cm^2, while for iron electrodes, they ranged from 4.75 mA/cm^2 to 12.36 mA/cm^2.

This relationship between current, current density, and voltage in electrochemical processes agrees with Ohm's law, which states that the voltage across a conductor is directly proportional to the current flowing through it. As observed, increasing the current leads to a corresponding increase in current density, which is crucial for understanding the efficiency and effectiveness of the electrochemical reactions taking place. The findings are consistent with those of Isarain-Chávez et al. (2014), who also observed a direct relationship between current and voltage in their electrochemical reactor, adhering to Ohm's law. This correlation is vital for optimizing the electrochemical treatment process, as it allows for precise

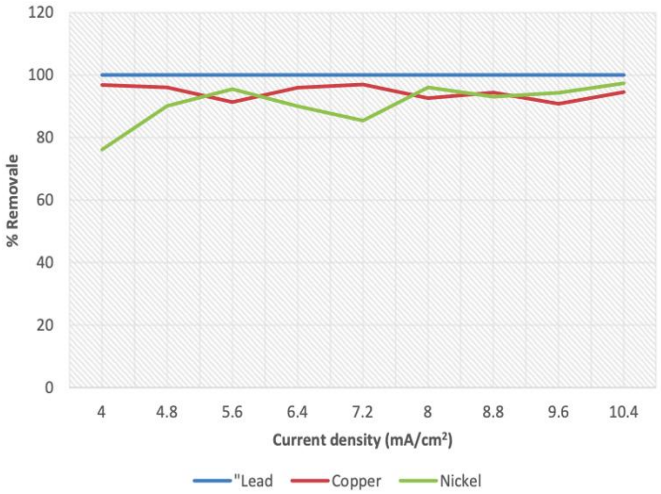

Figure 2. Plot of percentage removal of lead, copper, and nickel against current density for EC (Source: Authors' own elaboration)

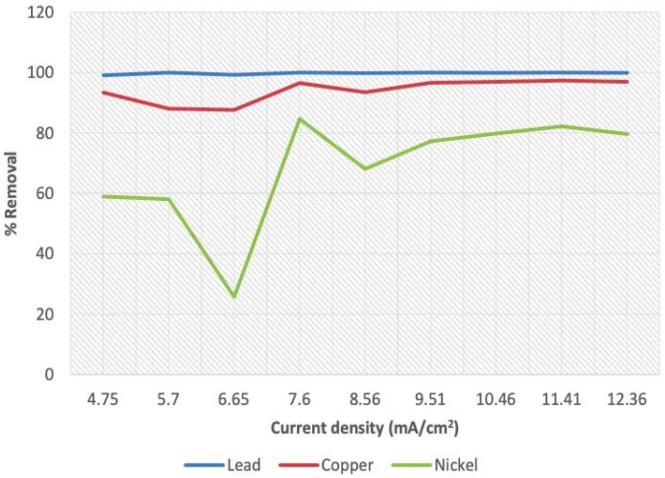

Figure 3. Plot of percentage removal of lead, copper, and nickel against current density for EO (Source: Authors' own elaboration)

control over the operational parameters to maximize contaminant removal while maintaining energy efficiency. However, higher density can lead to secondary reactions and increased colloid charge reversal, which may reduce treatment efficiency.

Percentage Removal

The metals considered in this work were zinc, lead, copper, and nickel; but, only lead, copper, and nickel underwent further analysis. The individual concentrations of the metals in the wastewater after the treatment were determined and used to calculate their percentage removal. A multiple bar chart and line graph were used to represent the data for the percentage removal of the metals at specific current densities.

The plots showing the effect of current density on lead, copper, and nickel are shown in **Figure 2**, **Figure 3**, and **Figure 4**.

The plots of **Figure 2**, **Figure 3**, and **Figure 4** show the relationship between the percentage removals of lead, copper, and nickel and current density.

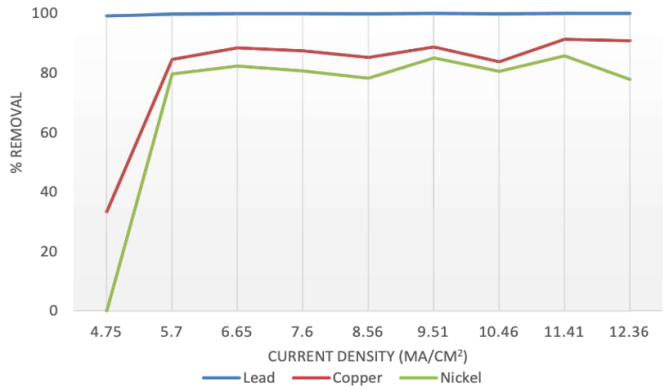

Figure 4. Plot of percentage removal of lead, copper, and nickel against current density for the combined EC-EO (Source: Authors' own elaboration)

Table 4. Effect of current density on lead and copper pollutants in the wastewater-1

Current density (mA/cm²)	Concentration of lead in wastewater after EC (mg/l)	Percentage removal of lead (%)	Concentration of copper in wastewater after EC (mg/l)	Percentage removal of copper (%)
4.00	0.00	100	0.066	96.76
4.80	0.00	100	0.081	96.04
5.60	0.00	100	0.177	91.30
6.40	0.00	100	0.083	95.95
7.20	0.00	100	0.061	97.02
8.00	0.00	100	0.151	92.58
8.80	0.00	100	0.114	94.40
9.60	0.00	100	0.187	90.81
10.40	0.00	100	0.111	94.55

Table 5. Effect of current density on nickel pollutant in the wastewater-1

Current density (mA/cm²)	Concentration of nickel in wastewater after EC (mg/l)	Percentage removal of nickel (%)
4.00	0.243	76.18
4.80	0.101	90.09
5.60	0.046	95.49
6.40	0.102	90.00
7.20	0.149	85.39
8.00	0.041	95.98
8.80	0.071	93.04
9.60	0.058	94.31
10.40	0.027	97.35

The data on EC, EO, and hybrid show the effect of current density on the removal of metals from the effluent water.

Table 4 shows that all current densities verified, lead was completely removed by EC from the effluent water. The best current densities for copper and nickel content removal, as shown in **Table 4** and **Table 5** were 7.20 mA/cm² and 10.40 mA/cm², respectively, producing a percentage removal of 97.02% and 97.35%. The experimental results obtained from this study have revealed that the optimal current densities for copper and nickel content removal were 7.20 mA/cm² and 10.40 mA/cm², respectively, achieving a percentage removal of 97.02% and 97.35%.

These findings is similar to previous research conducted by Hedeş et al. (2019), who demonstrated that an increase in the applied current density enhances the treatment rate and leads to a faster removal of pollutants.

Table 6. Effect of current density on lead and copper pollutants in the wastewater-2

Current density (mA/cm²)	Concentration of lead in wastewater after EO (mg/l)	Percentage removal of lead (%)	Concentration of copper in wastewater after EO (mg/l)	Percentage removal of copper (%)
4.75	0.014	99.14	0.134	93.42
5.70	0.000	100	0.244	88.01
6.65	0.012	99.26	0.251	87.65
7.60	0.000	100	0.071	96.51
8.56	0.003	99.82	0.133	93.46
9.51	0.001	99.94	0.069	96.61
10.46	0.002	99.88	0.062	96.95
11.41	0.000	100	0.054	97.35
12.36	0.002	99.88	0.062	96.95

Table 7. Effect of current density on nickel pollutant in the wastewater-2

Current density (mA/cm²)	Concentration of nickel in wastewater after EO (mg/l)	Percentage removal of nickel (%)
4.75	0.419	58.92
5.70	0.428	58.04
6.65	0.757	25.78
7.60	0.156	84.71
8.56	0.326	68.04
9.51	0.232	77.25
10.46	0.206	79.80
11.41	0.182	82.16
12.36	0.208	79.61

Table 8. Effect of current density on lead and copper pollutants in the wastewater-3

Current density (mA/cm²)	Concentration of lead in wastewater after EO (NTU)	Percentage removal of lead (%)	Concentration of copper in wastewater after EO (mg/l)	Percentage removal of copper (%)
4.75	0.013	99.20	1.356	33.37
5.70	0.004	99.75	0.314	84.57
6.65	0.001	99.94	0.235	88.45
7.60	0.002	99.88	0.255	87.47
8.56	0.003	99.82	0.301	85.21
9.51	0.000	100	0.229	88.75
10.46	0.003	99.82	0.330	83.78
11.41	0.000	100	0.176	91.35
12.36	0.000	100	0.187	90.81

With EO, **Table 6** and **Table 7** show that the best current density was 5.70 mA/cm² for lead, 11.41 mA/cm² for copper and 7.6 mA/cm² for nickel content removal, producing a percentage removalsof100%, 97.35% and 84.71%, respectively.

Table 8 shows the data for the hybrid of EC-EO, the best current density for lead was 9.51 mA/cm², 11.41 mA/cm² for copper, and 11.41 mA/cm² for nickel content removal, producing percentage removals of 100%, 91.35% and 85.78%, respectively. While a single pass of EC, EO, or combined EC-EO reduced the lead and copper to acceptable discharge limits, none succeeded in reducing nickel to its acceptable limit.

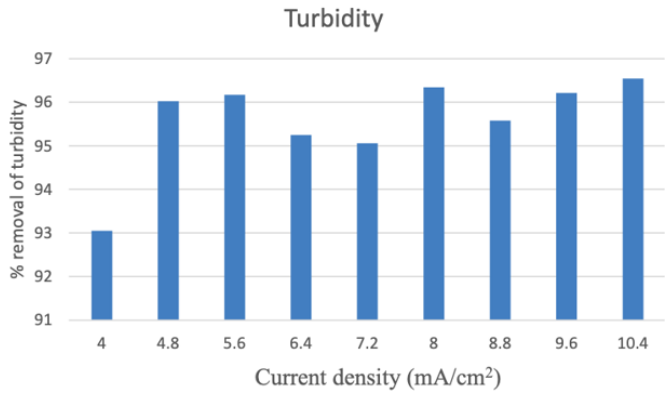

Figure 5. Effect of current density on turbidity using EC (Source: Authors' own elaboration)

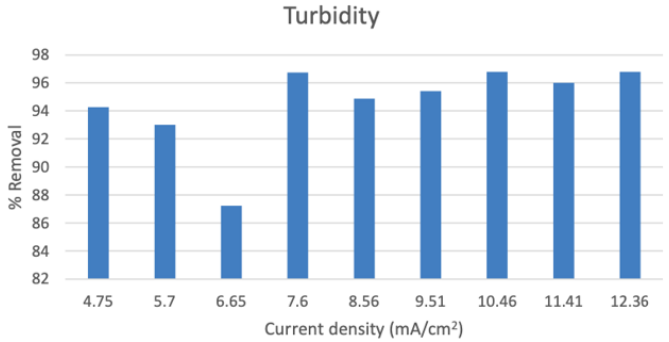

Figure 6. Effect of current density on turbidity using EO (Source: Authors' own elaboration)

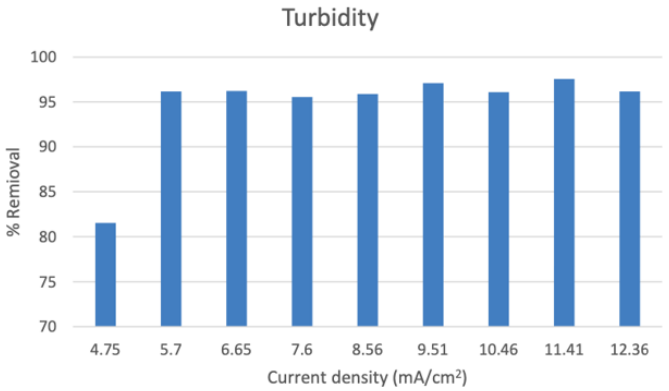

Figure 7. Effect of current density on turbidity using the combined EC-EO (Source: Authors' own elaboration)

Wastewater turbidity is given by the presence of colloidal species and suspended solids. The turbidity of the wastewater was reduced. TDS were also reduced.

Figure 5, **Figure 6**, and **Figure 7** show the plot of percentage reduction of turbidity of the wastewater against current density for EC, EO and the hybrid, respectively.

Table 9, **Table 10**, and **Table 11** show the combined effect of current density on turbidity and TDS with EC, EO and the hybrid. For EC, turbidity had a maximum reduction of 96.58% at the current density of 8.80 mA/cm^2.

These results suggest that current density is a critical factor in EC processes, influencing coagulant dosage, bubble generation rates, and pollutant removal rates. Higher current densities improve treatment efficiency, but also lead to secondary reactions and increased colloid charge reversal, which can reduce treatment efficiency (Zhang et al., 2013).

Table 9. Effect of current density on turbidity and TDS in the wastewater-1

Current density (mA/cm^2)	Turbidity of wastewater after EC (NTU)	Percentage removal of turbidity (%)	Concentration of TDS in wastewater after EC (mg/l)	Percentage removal of TDS (%)
4.00	13.906	93.05	152.98	84.31
4.80	7.955	96.02	129.96	86.67
5.60	7.663	96.17	119.97	87.70
6.40	9.510	95.25	125.16	87.16
7.20	9.878	95.06	118.58	87.84
8.00	7.325	96.34	117.53	87.95
8.80	8.844	95.58	125.00	87.18
9.60	7.575	96.21	112.96	88.41
10.40	6.930	96.54	83.37	91.45

Table 10. Effect of current density on turbidity and TDS in the wastewater-2

Current density (mA/cm^2)	Turbidity of wastewater after EO (NTU)	Percentage removal of turbidity (%)	Concentration of TDS in wastewater after EO (mg/l)	Percentage removal of TDS (%)
4.75	11.473	94.26	225.490	76.87
5.70	14.002	93.00	184.025	81.13
6.65	23.545	87.23	334.190	65.72
7.60	6.513	96.74	128.415	86.83
8.56	10.240	94.88	201.070	79.38
9.51	9.166	95.42	150.910	84.52
10.46	6.424	96.79	104.935	89.24
11.41	7.979	96.01	141.225	85.52
12.36	6.444	96.79	120.01	87.69

Table 11. Effect of current density on turbidity and TDS in the wastewater-3

Current density (mA/cm^2)	Turbidity of wastewater after EC-EO (NTU)	Percentage removal of turbidity (%)	Concentration of TDS in wastewater after EC-EO (mg/l)	Percentage removal of TDS (%)
4.75	36.949	81.53	462.92	52.52
5.70	7.677	96.17	73.00	92.51
6.65	7.588	96.21	67.46	93.08
7.60	8.913	95.54	55.50	94.31
8.56	8.223	95.89	81.58	91.63
9.51	5.818	97.09	56.48	94.21
10.46	7.813	96.09	64.96	93.33
11.41	4.884	97.56	56.99	93.67
12.36	7.677	96.16	81.58	90.94

While TDS had a maximum reduction of 91.45% at the current density of 10.40 mA/cm^2 and it experienced variations at some point, this behavior might be attributed to secondary reactions that occur at high current density, which lead to colloid charge reversal and thus cause re-dispersion of the colloids.

Moreover, higher current density could also result in a reduction of the electrode lifetime (Zhang et al., 2013). With EO, turbidity had a maximum reduction of 96.79% at current density of 9.51 mA/cm^2 while TDS had a maximum reduction of 89.24% at current density of 10.46 mA/cm^2. This result is

Table 12. Effect of current density on COD in the wastewater-1

Current density (mA/cm^2)	COD in wastewater after EC (mg/l)	Percentage reduction of COD (%)
4.75	379.120	10.21+
5.70	497.610	44.65+
6.65	0.001	99.99
7.60	158.750	53.85
8.56	171.560	50.13
9.51	0.002	99.99
10.46	0.000	100
11.41	0.000	100
12.36	0.002	99.99

Table 13. Effect of current density on COD in the wastewater-2

Current density (mA/cm^2)	COD in wastewater after EC-EO (mg/l)	Percentage increase of COD (%)
4.75	4,127.44	1,099.87
5.70	1,149.05	234.026
6.65	1,481.89	330.78
7.60	1,180.21	243.08
8.56	1,116.46	224.55
9.51	1,081.52	214.40
10.46	1,395.78	305.75
11.41	1,309.51	280.67
12.36	931.91	170.94

similar to that conducted by Prazeres et al. (2020) that examined the effect of oxidant concentration on the reduction of turbidity in cheese whey wastewater. Compared to EO, which achieved a maximum turbidity reduction of 96.79% at a current density of 9.51 mA/cm^2, the oxidant-based treatment achieved a maximum reduction of 90% at higher concentrations of oxidant (2-3 g/L)

However, higher concentrations of oxidant (4-6 g/L) resulted in reduced efficiency, suggesting that there is an optimal range of oxidant concentration for turbidity removal. For hybrid of EC/EO, turbidity had a maximum reduction of 97.56% at the current density of 11.41 mA/cm^2 while TDS had a maximum reduction of 94.31% at current density of 7.60 mA/cm^2. It was only the hybrid EC-EO that reduced the turbidity to within an acceptable discharge limit. A similar study by Asfaha et al. (2022) examined the effectiveness of hybrid EC-EO for turbidity and TDS reduction. Asfaha et al.'s (2022) study found that the hybrid EC-EO process achieved a maximum turbidity reduction of 97.35% at a current density of 11.41 mA/cm^2 and a maximum TDS reduction of 93.54% at a current density of 7.60 mA/cm^2.

The maximum COD percentage removal was 99.16% at a current density of 2.89 mA/cm^2 experienced with EC. This could be attributed to the fact that the current density controls the speed of dissolution of the anode (anodic process) as well as the speed of hydrogen production (cathodic process). The influence of the variation of this parameter (between 6.4 and 10.4 A/m^2) was examined on the efficient removal of COD. It is important to bear in mind that the higher the density of the current, the smaller the bubble size (Malakootian & Yousefi, 2009). Therefore, there is an increase in the contact area between the gas (H_2) and the pollutants and the speed of removal of the contaminants is favored, and the efficiency of the flotation increases (Pudi et al., 2022).

Table 12 (COD removal using EO) shows maximum percentage removal at 100% for both current densities of 10.46 mA/cm^2 and 11.41 mA/cm^2; This is due to the higher number of ions produced on the electrodes promoting destabilization of the pollutant molecules. Conversely at current densities of 4.75 mA/cm^2 and 5.70 mA/cm^2 percentage increase in COD was observed, which is almost same for color removal efficiency.

Table 13 (COD removal using the hybrid of EC-EO) shows that COD increased at all current densities, similar to the result observed by Prazeres et al. (2020) in their study of reduction of total phenols, total phosphorus and turbidity by un-catalytic oxidation processes in cheese whey wastewater. During EO with iron electrodes, iron ions were greatly deposited on the wall of the container and in the wastewater causing corroboration too; with this accumulation of matter, electrode performance was reduced, and high COD levels were seen. Problems associated with operational issues may include equipment malfunction, equipment having previous results that were not cleaned off and insufficient mixing of the wastewater during EO. Human error can occur as a result of inadequate maintenance of treatment facilities.

A hybrid treatment approach combining EC and EO was implemented at the ETP of the NBC in Owerri, Nigeria, in an effort to address wastewater quality issues. The study revealed that despite meeting the discharge standards for dissolved oxygen and zinc, the wastewater was in violation of numerous other standards. Optimal treatment times were determined to be 20 minutes for EC and 30 minutes for EO, which agreed with previous research. Current density was also found to be a critical factor, influencing the removal efficiency of contaminants. Through EC, lead was completely removed from the wastewater, while copper and nickel concentrations were significantly reduced. EO showed promising results as well, particularly in decreasing turbidity and TDS levels. When the hybrid EC-EO approach was applied, turbidity was reduced to acceptable discharge limits, and TDS was also significantly reduced. However, a notable increase in COD was observed during the treatment (up to 1099.87%). This increase can be attributed to several factors, including operational issues such as electrode deposition, which may lead to the release of organic materials back into the solution, and inadequate mixing, which can result in uneven distribution of reactants and hinder the overall treatment efficiency. To address this issue, it is essential to optimize the operational parameters, such as increasing the mixing intensity and frequency of electrode cleaning, to minimize deposition. Also, exploring alternative electrode materials that are less prone to fouling could further enhance the treatment process. Despite these challenges, the study demonstrated the importance of process optimization and highlighted the potential of hybrid EC-EO as a viable treatment method for industrial wastewater.

CONCLUSION

In conclusion, the application of EC and EO for the treatment of effluent water from the NBC process plant in Owerri has shown significant promise in addressing the challenges posed by wastewater pollution. The study revealed

that the effluent water from the plant was highly polluted, exceeding the discharge standards set by the NESREA in several physicochemical parameters. However, through the hybrid approach of EC and EO, notable improvements were achieved in reducing contaminants to within acceptable limits. The optimization of treatment times and current densities proved crucial in enhancing treatment efficiency, with EC proving effective in removing lead, copper, and nickel, while EO demonstrated effectiveness in reducing turbidity and TDS. Additionally, the hybrid EC-EO approach yielded the most favorable results, particularly in meeting acceptable discharge limits for turbidity. However, challenges such as an increase in COD during hybrid treatment were observed, highlighting the need for further investigation into operational issues affecting treatment efficacy. While EC proved to be effective in removing heavy metals, EO excelled in reducing turbidity and TDS levels. The hybrid EC-EO approach further increased treatment efficacy, meeting acceptable discharge limits for turbidity. However, operational issues such as inadequate mixing and electrode deposition require further investigation to fully understand and address the observed COD increase during hybrid treatment. Future studies should focus on systematically investigating factors like electrode deposition, mixing intensity and frequency, and electrode materials to develop a more effective EC-EO hybrid treatment method. In addition to the demonstrated effectiveness of the combined EC and EO method in treating wastewater from the Industrial Process Plant in Owerri, it is essential to consider the broader applicability and economic feasibility of this hybrid approach in various industrial wastewater treatments. Numerous studies have highlighted the versatility of EC and EO in addressing a wide range of contaminants, including heavy metals, organic pollutants, and turbidity, across different industrial sectors such as textile, pharmaceutical, and food processing industries. For instance, research by Ahmad et al. (2018) and Singh et al. (2023) has shown that these methods can significantly reduce pollutant levels in textile effluents and pharmaceutical wastewater, respectively, achieving compliance with environmental discharge standards. Moreover, the economic feasibility of implementing the EC-EO hybrid method can be enhanced through the optimization of operational parameters, such as current density and treatment time, as demonstrated in this study. The potential for reduced chemical usage and lower sludge production compared to conventional treatment methods further supports its economic viability. Future research should focus on pilot-scale studies to evaluate the long-term performance and cost-effectiveness of this hybrid approach in diverse industrial settings.

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