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Efficient degradation of phenol by electrooxidation process at boron-doped diamond anode system

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ABSTRACT

The rapid increase in global population and industrialization has led to increased environmental pollution, primarily due to insufficient treatment technologies and the depletion of freshwater resources. This research investigates the impact of the electrooxidation (EO) process using Boron Doped Diamond (BDD) anode on phenol degradation, energy consumption, total operating costs, and anode efficiency. The study was carried out on different current densities (j = 50-200 A/m^2), initial pH (3.6-9.6), initial phenol concentration (C_i = 100-800 mg/L), and supporting electrolyte concentration (SEc = 2-6 g NaCl/L). The phenol removal efficiency under optimum conditions (anode = BDD, j = 200 A/m^2, initial pH = 7.6, C_{phenol} = 100 mg/L, and SE_c = 4 g NaCl/L) was determined to be 100% after 50 min of EO reaction time. However, the energy consumption and total operating cost under these conditions were 12.7 kWh/m^3 (420 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol), respectively. Moreover, BDD anode efficiencies were calculated as 6.39, 3.47, and 1.74 g phenol/Ahm^2 at current densities of 50, 100, and 200 A/m^2, respectively. Consequently, the EO process is a more cost-effective treatment approach for efficient phenol removal from an aqueous solution.

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1. Introduction

With the increasing population and developing technology, industrial capacity is increasing. This increases the consumption of natural resources and water. Water consumed in industrial areas returns to nature as polluted water [1]. Phenol compounds are generally found in significant amounts in wastewater from the paper industry [2] and olive oil production facilities [3], oil refineries [4], [5], coke ovens [6], textile production facilities [7], iron and steel mills [8], and gas production facilities [9]. Therefore, it has become mandatory to treat wastewater in a way that prevents the pollution of natural water resources [10]. Phenols, especially in the structure of industrial wastewater, are persistent aromatic organic compounds in which one or more hydroxyl groups are attached to the aromatic ring [11]. International regulatory agencies have established stringent limits on phenol discharge into the environment; for instance, the United States Environmental Protection Agency (USEPA) has mandated that phenol content in surface water must not exceed 1 ppb [12]. Phenol, which considerably impacts water quality, is unpleasant even at minimal concentrations. A phenol content of 2.5 mg/L results in an unpleasant taste and odor [13]. High concentrations terminate all vital environmental activities [14]. Due to its harmful effects, it is among the primary pollutants.

Therefore, the efficient treatment of phenol-contaminated water is of great importance for human and environmental health [15]. One of the most significant issues in wastewater management is the development of efficient treatment methods that can efficiently eliminate contaminants and mitigate their toxicity to organisms [16,17]. In the existing literature, different treatment processes have been used to remove phenol wastewater, such as distillation [18], adsorption [19,20], chemical oxidation [21], enzymatic treatment [22], membrane technology [23,24], electrooxidation [25], electro-Fenton [26], and photocatalytic process [27]. Although these processes are efficient in phenol removal, their use is not recommended for phenol removal [28]. For example, one of the major drawbacks of using extractive membrane bioreactors for phenol removal is that the combination of several systems requires a large area and many variables need to be adjusted frequently [29]. The use of reverse osmosis and nanofiltration technology for phenol removal is more suitable for treating water with low phenol concentrations but not for high concentrations and is difficult to choose because it requires replacement of the fouled membrane or chemical cleaning [23]. On the other hand, membrane distillation is not recommended for phenol removal due to poor phenol separation due to limited membrane selectivity, and the high cost of setting up the system [30]. Therefore, there is a need for a process for phenol oxidation that does not have these disadvantages [28]. Recently, electrooxidation (EO), as one of the electrochemical methods, has been a highly efficient process for phenol removal [25]. When subjected to an electrical current, hazardous or non-biodegradable chemicals undergo oxidation, resulting in their transformation into biodegradable compounds or total oxidation into carbon dioxide (CO_2), water (H_2O), and readily degradable organic molecules [31,32]. The EO process offers several advantages in the degradation of organic substances. These include a notably high level of efficiency, as it effectively breaks down organic compounds [33]. Additionally, EO does not require the addition of chemical reagents, which simplifies the treatment process. The use of EO also leads to significantly reduced retention times, preventing the formation of sludge [10,34]. Furthermore, EO can be seamlessly integrated into existing treatment processes due to its straightforward structural design, the process is also easily controlled, making it manageable for operators [6]. Lastly, EO is environmentally friendly, as the primary reagent used possesses electron properties that contribute to its eco-friendliness [35-37].

This study seeks to assess the impact of BDD anode on phenol removal across different current densities, initial pH, phenol concentrations, and supporting electrolyte concentrations through the EO process. Furthermore, specific energy consumption (in kWh/m^3 and kWh/kg phenol removal), total operating costs (\$/m^3 and \$/kg phenol removed), and anode efficiency (in g phenol removal/Ahm^2) were evaluated.

2. Materials and methods

2.1. Materials and chemicals

The investigation employed high-quality chemicals, all of which were obtained from Merck (Germany). However, phenol was obtained from Kimya Borsası (Turkey). In the EO process, the anode used in this study is a BDD, which is composed of a layer of boron diamond film deposited on a 1.5 mm niobium plate (Nb/BDD) obtained from DiaCon GmbH, Germany. The cathode is made of stainless steel (SS) sourced from Turkey (316 AISI SS). The tap water used in the study was measured as initial pH (7.60), temperature (T, 13 °C), electrical conductivity (420 µs/cm), total hardness (310 mg HCO_3^-/L), total dissolved solids (TDS, 220 mg/L), magnesium (Mg^{2+}, 68 mg/L), calcium (Ca^{2+}, 102 mg/L), sodium (Na^+, 94 mg/L), potassium (K^+, 11 mg/L), chloride (Cl^-, 78 mg/L), and sulfate (SO_4^{2-}, 175 mg/L). However, the phenol synthetic stock solution was prepared by dissolving the required amount of phenol in tap water.

2.2. Experimental setup and procedure

All EO experiments were performed in a cylindrical batch glass reactor (V = 750 mL, diameter = 10 cm, and height = 12.5 cm). In the EO experiments, rectangular anode and cathode plate electrodes used were of the same size (length = 20 cm, width = 6 cm, and thickness 3 mm). The length of the contact area of the electrodes in the effluent in the EO reactor is = 10 cm, the distance between the electrodes is 1.5 cm, and the active surface area of the anode electrode is 0.012 m^2. The electrodes in the reactor were placed vertically, parallel to each other. The electrodes were fixed 1.5 cm above the bottom of the EO reactor. For each experimental study, 550 mL of wastewater was used. In the EO process, after the electrodes were connected to the respective (+) or (-) poles of the power supply (Gwinstek DC SPS-606, 0-6 A and 0-60 V), the required current and voltage settings were made. During the operational period, water was agitated using a magnetic stirrer set at a rotational speed of 250 rpm. Samples were taken from the EO reactor at different operating times, each sample was passed through a 0.45 mm membrane filter before analysis. Then, phenol and output pH analyses were performed. All experiments of the EO process were carried out at room temperature (25 ± 1 °C). A schematic representation of an EO reactor is given in (Figure. 1).

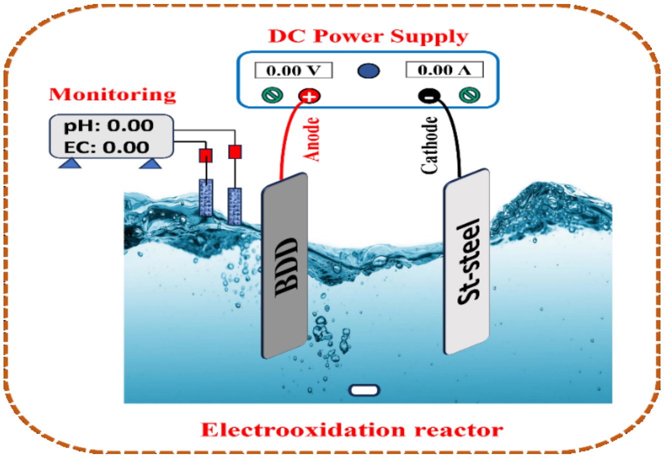


Figure 1. *Schematic representation of the electrooxidation process.*

2.3. Analytical methods

All experiments were assessed using the Standard Method guidelines for water and wastewater analysis [38]. A UV-vis spectrophotometer (Helios, Thermo Aquamate 2000E, UV-Vis spectrometer) was used to measure the absorbance of the colored phenol 4-aminoantipyrine complex at a wavelength of 500 nm. The absorbance value obtained was then compared with the calibration curve. The pH and conductivity were measured using the Thermo Scientific Eutech pH 150 (Singapore) and YSI model 30 (USA). The analyses were performed in duplicates, and the data averages were reported if the test error was below 1%.

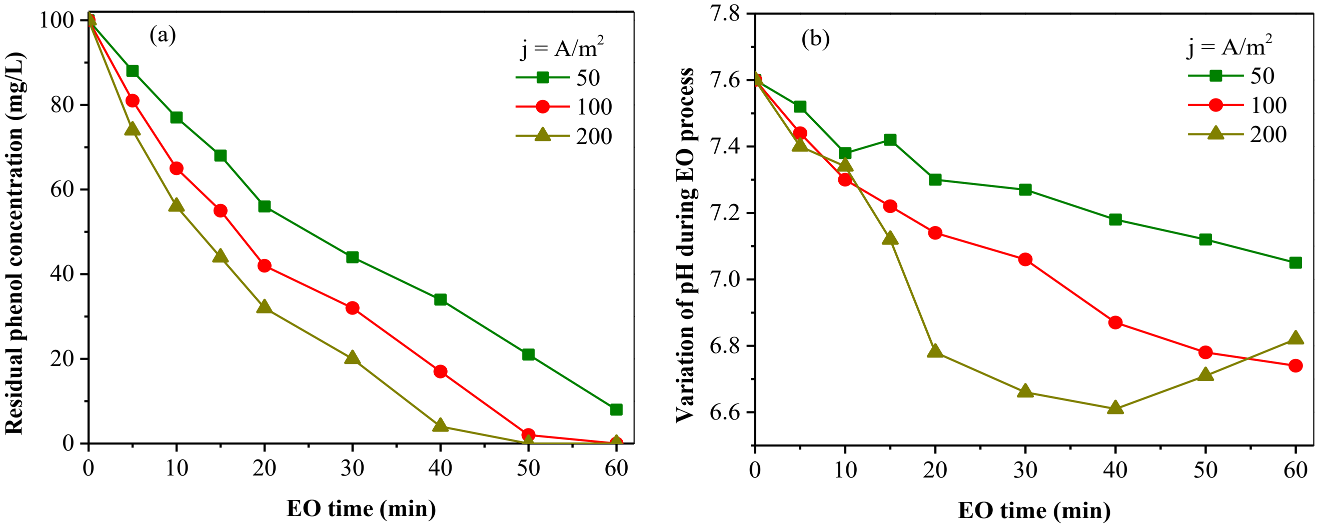
3. Results and discussion

3.1. Impact of current density

The current density is often considered the principal variable in the EO process because of its impact on the reaction rate. Current density is calculated by dividing a specified current (i) by the associated effective electrode surface area ($j = i/A_{electrode}$, A/m^2, or mA/cm^2) [31,37,39]. As shown in (Figure. 2a), under optimum conditions (anode = BDD, initial pH = 7.6, C_i = 100 mg/L, and SE_c = 6 g NaCl/L), the phenol output concentration was calculated as 8 mg/L (92.0%) after 60 min at 50 A/m^2, and 0.001 mg/L (100%) after 60 min at 100 A/m^2, and 0.001 mg/L (100%) after 50 min at 200 A/m^2, respectively. The study by Amado-Piña et al. (2017) calculated 98% on the removal of 100 mg/L phenol under optimum conditions such as anode = BDD, pH = 7.0, j = 600 A/m^2, and room temperature [40]. The results demonstrate a clear relationship between current density and removal efficiency, with an observed increase in removal efficiency as current density increases [10]. This suggests a positive correlation between current density and both mass transport and phenol concentration [41]. This correlation may be attributed to the enhanced generation of $^{\bullet}$OH radicals during the oxidation process, which potentially contributes to a higher level of efficiency in the removal process [42]. It is crucial to recognize that augmenting the current density does not always result in enhanced efficiency or oxidation rates. The effect of current density on removal efficiency, particularly for a certain anode material, is contingent upon the distinct properties of the effluent or aqueous medium requiring treatment [37]. Conversely, using larger current densities often leads to elevated operational expenses as a consequence of increased energy consumption [33]. The poor adsorption of hydroxyl radicals, which exhibit high reactivity towards organic molecules, may be attributed to the inert surface of the BDD anode [10]. The BDD anode may be characterized as a "non-active" anode due to its lack of catalytically active sites for the adsorption of reactants and/or products in an aqueous medium [33]. Therefore, non-active anodes, such as BDD, are considered favorable electrodes for fully oxidizing organic compounds to H_2O and CO_2 Eqs (1-3).

$$BDD + H_2O \rightarrow BDD(\bullet OH) + H^+ + e^- \quad (1)$$
$$BDD(\bullet OH) + R \rightarrow BDD + mCO_2 + nH_2O \quad (2)$$
$$BDD(\bullet OH) \rightarrow BDD + 0.5O_2 + H + e^- \quad (3)$$

Another important parameter in the EO process is the change of pH during the process stage [6], as can be seen in (Figure. 2b), from the optimum pH = 7.60, after 60 min at current densities of 50, 100, and 200 A/m^2 the final pH values decreased from 7.60 to 7.05 for 50 A/m^2, from 7.60 to 6.74 for 100 A/m^2, and from 7.60 to 6.24 for 200 A/m^2, respectively. As it can be seen from (Fig. 2a), the concentration of phenol remaining after 50 min at current densities of 100 and 200 A/m^2 was calculated to be 2 and 0.001 mg/L, it can be said that increasing the current density from 100 to 200 A/m^2 has a relatively weaker effect on phenol removal, which is explained by the fact that the removal of phenol is slower in acidic environments of pH. Another important parameter is the voltage (V) variation of the cell in the EO process because it is the most important parameter affecting the energy consumption in the EO process, as can be seen from (Figure. 2c), the applied V values after 1 hour at different current densities of 50, 100, and 200 A/m^2 using electrolyte with a constant 4 g/L NaCl support changed from 8.80 to 8.87 for 50 A/m^2, from 9.30 to 9.34 for 100 A/m^2, and from 10.50 to 10.25 for 200 A/m^2, respectively. Moreover, BDD anode efficiencies (as calculated by Eq. 9) were calculated as 6.39, 3.47, and 1.74 g phenol/Ahm^2 at current densities of 50, 100, and 200 A/m^2, respectively



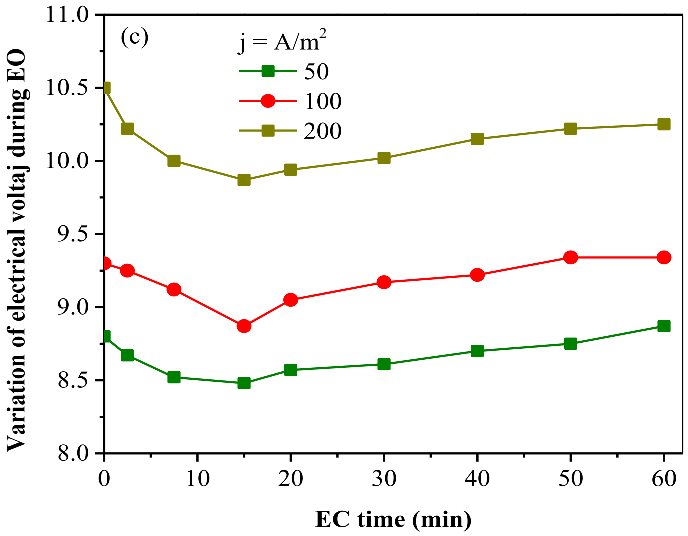


Figure 2. *Impact of different current densities on (a) phenol removal, (b) initial pH variation, and (c) electrical voltage variation*

Energy consumption and cost-effectiveness of the EO process are crucial criteria for the adoption of wastewater treatment technologies in industrial applications. The main cost components associated with the treatment of phenol-contaminated wastewater by the EO process are electricity consumption and the use of chemicals. The energy consumption (as kWh/m^3) for the EO process, the magnetic stirrer, and the total energy consumption for the process were calculated using Eqs. (4-6), respectively. However, the specific energy consumption (SEC) is the amount of energy used per unit mass of phenol removed from wastewater (in kWh/kg phenol). The SEC for phenol was determined using Eq. (7).

$$C_{energy}\ (\mathrm{kWh/m^3}) = \frac{i \times t \times U}{v} \tag{4}$$

$$C_{magnetic\ stirrer\ energy}\ (\mathrm{kWh/m^3}) = \frac{N \times t}{v \times \eta\ (\%)} \tag{5}$$

$$C_{total\ energy}\ (\mathrm{kWh/m^3}) = C_{energy} + C_{magnetic\ stirrer\ energy} \tag{6}$$

$$\mathrm{SEC}\ (\mathrm{kWh/kg\ phenol}) = \frac{i \times t_{EO} \times U}{phenol_{rem}} \tag{7}$$

$$OC_{EO}\ (\$/\mathrm{m^3}) = \alpha \times C_{energy} + \beta \times C_{chemicals} \tag{8}$$

where i is the applied current (amperes, A), U is the cell voltage (volts, V), t is the duration of the EO process (in hours), v is the volume of treated wastewater (in m^3), and phenol$_{rem}$ is the phenol removed from the solution.
The total operating cost for the EO process was determined by using Eq. (8).

where α indicates the unit cost of electrical energy, C_{energy} indicates the total energy consumption related to the operations, β indicates the unit prices of chemicals, and $C_{chemical}$ symbolizes the quantities of chemicals used (in kg). In March 2025, Kyrgyzstan's market recorded an electrical energy price of 0.062 $/kWh. The unit costs for the chemicals used in the research were as follows: NaOH had a unit price of 0.40 $/kg; HCl had a unit price of 0.45 $/kg; and NaCl had a unit price of 0.05 $/kg [43].

During the EO process, the anode efficiencies (η) represent the amount of phenol removed (g) from
the wastewater per hour, per ampere, and per square meter. The anode efficiencies (η) for phenol were determined using Eq. (9). The $S_{electrode}$ is the active anode area inside the EO reactor.

$$\eta\ (\mathrm{g\ phenol/Ahm^2}) = \frac{(phenol_i - phenol_t) \times v}{i \times S_{electrode}} \tag{9}$$

The applied current, EO duration, and voltage between the anode and cathode directly determine the energy used in the EO process [37]. As can be seen from (Figure. 3), the specific energy consumption (SEC) and total operating costs (OC), under optimum conditions (anode = BDD, pH = 7.60, C_i = 100 mg/L, C_i = 100 mg/L, and SE_c = 4 gNaCl/L) for three different current densities were calculated as 3.73 kWh/m^3 (123. 2 kWh/kg phenol) and 0.43 $/m^3 (2.31 $/kg phenol) for 50 A/m^2, and 6.75 kWh/m^3 (233.2 kWh/kg phenol) and 0.62 $/m^3 (4.19 $/kg phenol) for 100 A/m^2, and 12.71 kWh/m^3 (420.0 kWh/kg phenol) and 0.99 $/m^3 (7.88 $/kg phenol) for 200 A/m^2, respectively. As can be seen from the results, the SEC and total OC of oxidation of the phenol increased with higher current densities. This resulted from the elevated electrical energy consumption resulting from the increased applied current density. Conversely, the efficiency of the anode decreased as the current density increased. Increasing the current density should enhance the removal of contaminants. However, it is expected that the current efficiency will decrease as a result of mass transport limits [37]. The results show that the 50 A/m^2 has the lowest SEC and total OC, while the 200 A/m^2 has the highest SEC and total OC.

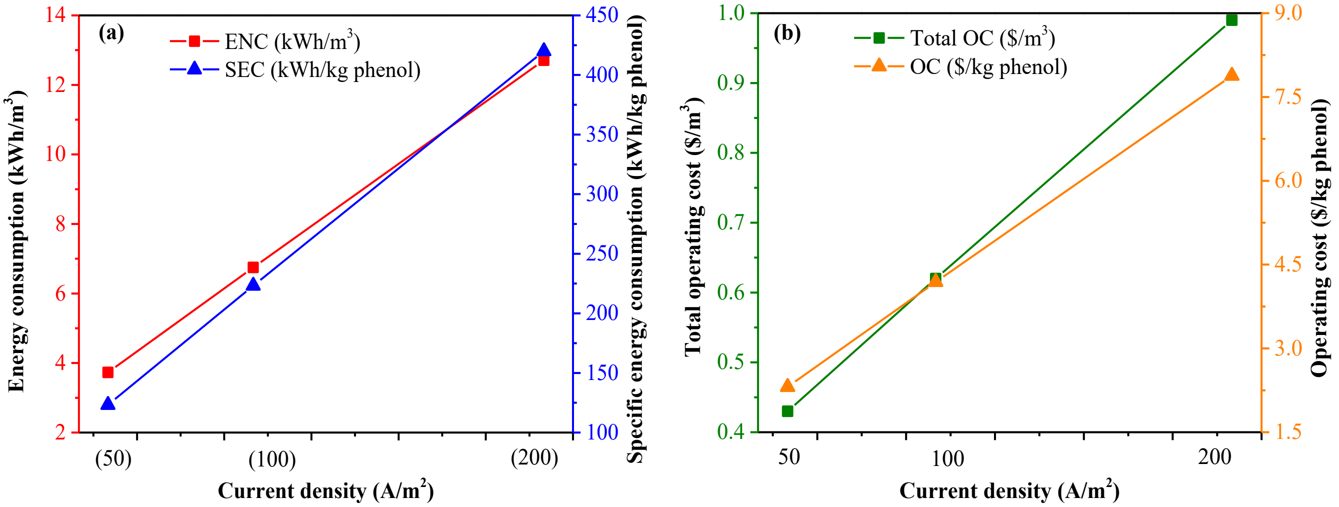


Figure 3. *Impact of different current densities on (a) specific energy consumption and (b) total operating costs.*

3.2. Impact of initial pH

The only controlled parameter in the EO process is pH, so the initial pH of the study is the most important parameter affecting the process efficiency [6]. As seen from (Figure. 4a), the phenol output concentration at different pH values between 3.6 and 9.6 under optimum conditions (anode = BDD, j = 200 A/m^2, C_i = 100 mg/L, and SE_c = 4 g NaCl/L) were calculated as 6 mg/L (Re = 94%) for pH 3.6 after 60 min, and 0.001 mg/L (Re = 100%) for pH 5.6 after 60 min, and 0.001 mg/L (Re = 100%) for pH 7.6 after 50 min, and 0.001 mg/L (Re = 100%) for pH 9.6 after 60 min, respectively. The results showed that the optimum pH for phenol removal by the EO process was 7.6. This indicates that degradation with the BDD anode was successful throughout a wide spectrum of pH values, implying that pH adjustment is unnecessary, provided that the pH is not above 9.6 [44]. As a result, the expenses related to treatment will decrease in actual implementations. The results demonstrate that the removal efficiency of all selected pollutants in phenol was optimal at an initial pH of 7.6 and markedly diminished under very acidic (pH 3.6) and alkaline (pH 9.6) conditions. The efficacy of phenol elimination decreased under acidic circumstances because of the instability of $OH^•$ radicals. However, it markedly improved in alkaline solutions due to the generation of OCl^- ions, indicating that natural or basic pH values were more favorable [45]. In acidic conditions, the reverse reaction takes place, resulting in the combination of OCl^- and H^+ ions to form $HOCl^-$ (as shown in Eqs. 10 and 11). Consequently, OCl^- ions demonstrate a propensity for an alternative reaction rather than oxidizing the pollutants, mostly due to their intrinsic instability [46]. Moreover, acidic conditions substantially reduce the concentration of important oxidative radicals, such as $^•OH$ radicals, produced at the anodes [45]. Furthermore, several chlorine species, including OCl^- and Cl_2, may be converted into ClO_3 Eq (12) or ClO_4 Eqs (13–16) under very alkaline conditions. These ions possess a restricted ability to oxidize and eliminate organic compounds. These characteristics together account for the decreased effectiveness of EO in alkaline conditions [47].

$$2Cl \rightarrow Cl_2 + 2e^- \quad (10)$$
$$Cl_2 + H_2O \rightarrow HOCl^- + Cl^- + H^+ \quad (11)$$
$$HOCl^- + H_2O \rightarrow 2ClO_3 + 4Cl^- + 12H^+ + 1.5O_2 + 6e^- \quad (12)$$
$$Cl^- + OH^- \rightarrow OCl^- + H^+ + e^- \quad (13)$$
$$OCl^- + OH^- \rightarrow ClO_2 + H + e^- \quad (14)$$
$$ClO_2 + OH^- \rightarrow ClO_3 + H + e^- \quad (15)$$
$$ClO_3 + OH^- \rightarrow ClO_4 + H + e^- \quad (16)$$

On the other hand, the outlet pH of the effluent after the EO process is important for the receiving environment, as can be seen from (Figure. 4b), the outlet pH after the EO process was 4.12, 5.37, 6.82, and 8.15 for the initial pH of 3.6, 5.6, 7.6, and 9.6, respectively. The results show that the initial pH of the study (7.6) is optimal because changing the initial pH of the solution requires the use of additional chemicals, which increases operating costs. Therefore, it is more advantageous to conduct the study at an initial pH of 7.6.

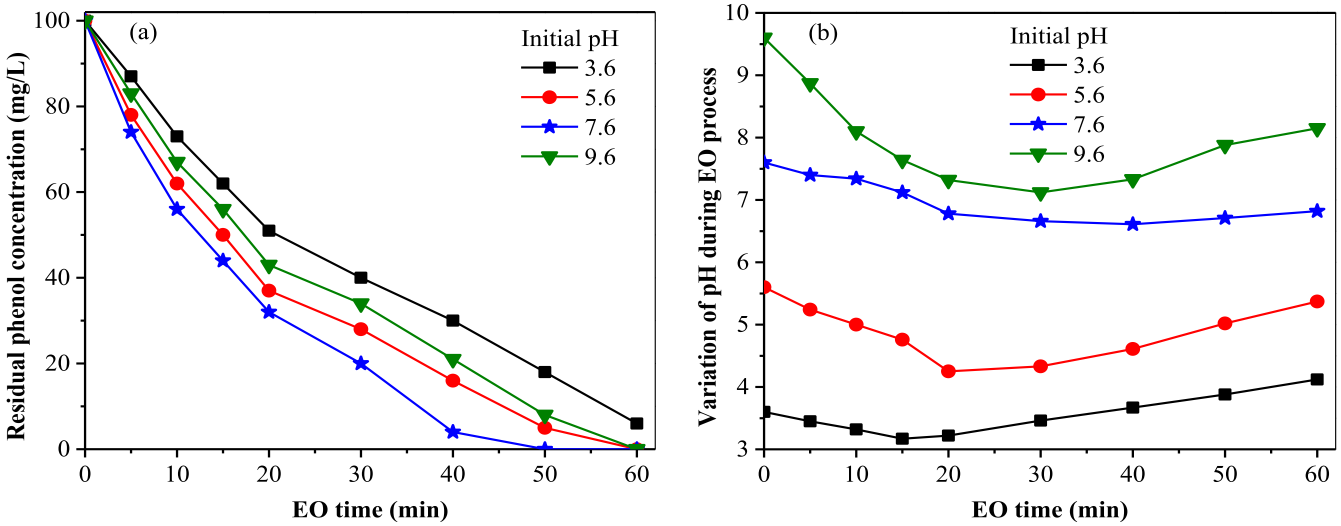


Figure 4. *Impact of initial pH on (a) phenol removal and (b) pH variation during the process.*

As can be seen from (Figure. 5), under optimum conditions (anode = BDD, j = 200 A/m^2, C$_i$ = 100 mg/L, and SE$_c$ = 4 gNaCl/L) the SEC and total OC were calculated as 16.6 kWh/m^3 (548.8 kWh/kg phenol) and 1.38 \$/m^3 (10.3 \$/kg phenol) for pH of 3.60, and 14.8 kWh/m^3 (489.6 kWh/kg phenol) and 1.22 \$/m^3 (9.18 \$/kg phenol) for pH of 5.60, and 12.7 kWh/m^3 (420.0 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol) for pH of 7.60, and 15.3 kWh/m^3 (496.8 kWh/kg phenol) and 1.18 \$/m^3 (9.32 \$/kg phenol) for pH of 9.60, respectively. As can be seen from the results, the lowest SEC and total OC were obtained at the optimum pH of the study. This is due to the cost of the chemicals used in the other pH, and also due to the slower removal of phenol, which requires longer time in the rectifier, which leads to high energy consumption, resulting in high operating cost of the study [6].

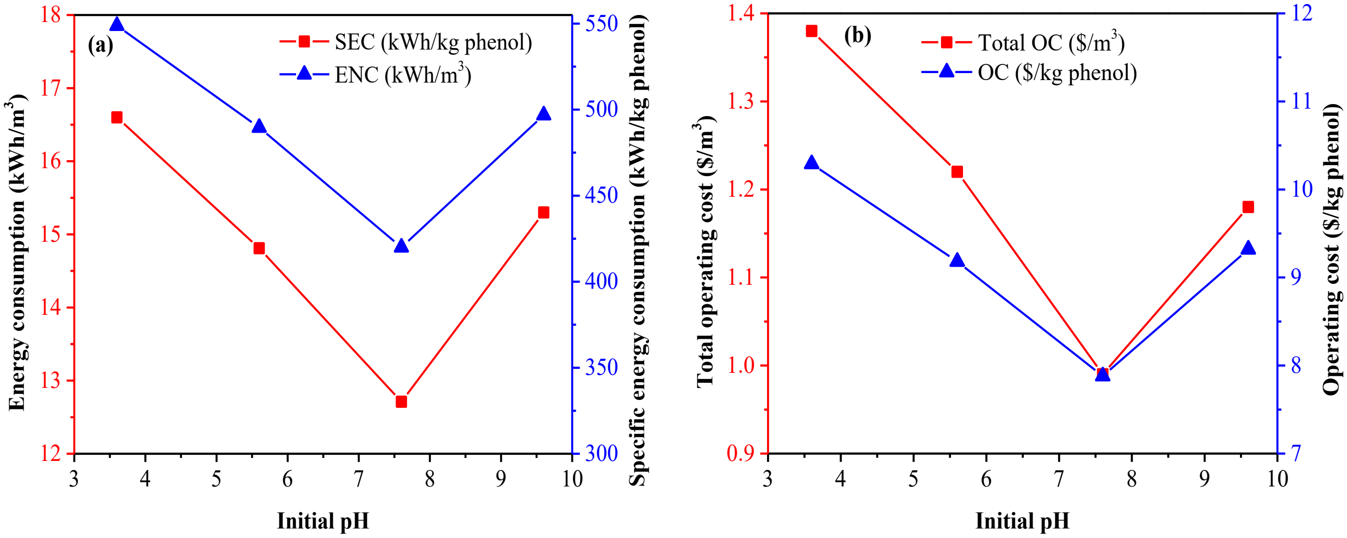


Figure 5. *Impact of initial pH on (a) specific energy consumption and (b) total operating costs.*

3.3. Impact of phenol concentration

The initial phenol concentration is the most important parameter because higher concentrations require longer times for degradation by the EO process [48]. In this study, experiments were performed with different phenol starting concentrations of 100, 200, 400, and 800 mg/L under optimum conditions (anode = BDD, j = 200 A/m^2, C$_i$ = 100 mg/L, and SE$_c$ = 4 g/L). As can be seen from (Figure. 6), the time required for 100% phenol removal was calculated as 50, 120, 160, and 240 min, respectively. As can be seen from the results, higher phenol concentrations require a longer time in the reactor for degradation.

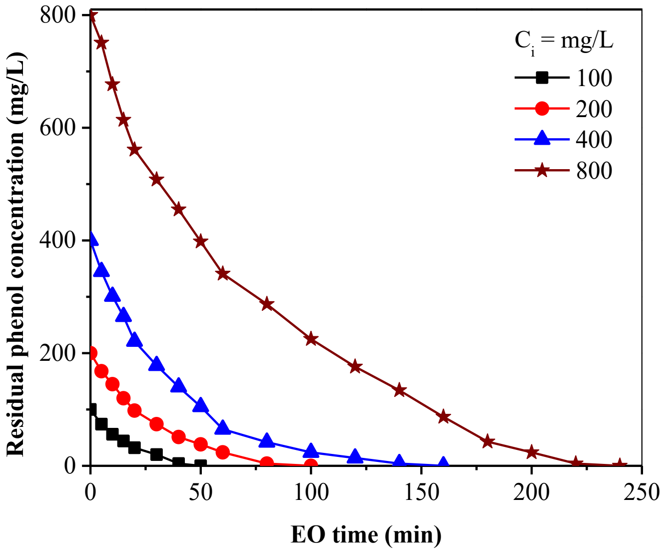


Figure 6. *Impact of reaction time on different phenol concentration removal.*

As can be seen from (Figure. 7), the SEC and total OC required under optimum conditions (anode = BDD, j = 200 A/m^2, SEc = 4 gNaCl/L) for removal of different phenol concentrations were calculated as 12.7 kWh/m^3 (420 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol) for 100 mg/L of phenol, and 25.41 kWh/m^3 (420 kWh/kg phenol) and 1.78 \$/m^3 (7.88 \$/kg phenol) for 200 mg/L of phenol, and 35.2 kWh/m^3 (291.2 kWh/kg phenol) and 2.38 \$/m^3 (5.46 \$/kg phenol) for 400 mg/L of phenol, and 52.9 kWh/m^3 (218.4 kWh/kg phenol) and 3.48 \$/m^3 (4.10 \$/kg phenol) for 800 mg/L of phenol, respectively. As can be seen from the results, the lowest SEC and total OC were obtained for the low phenol concentration of the study. This is due to the fact that other phenol concentrations require longer time to be reconciled, which leads to high energy consumption, resulting in high operating cost of the study [48].

3.4. Impact of supporting electrolyte concentration

The use of a supported electrolyte increases the conductivity of the solution and the cell voltage decreases, thus leading to lower energy consumption, and lower energy consumption minimizes the total operating cost of the process [49].

In the existing literature, different supported electrolytes were used for phenol oxidation in the EO process, of which NaCl was found to be the most efficient [50,51]. In this study, different concentrations of NaCl were used as supporting electrolytes. Another important reason is that using NaCl as a supported electrolyte, $HOCl^-$ (as seen in Eqs. 10 and 11), is formed rapidly with sodium chloride as a supporting electrolyte and will play an important role in phenol oxidation [50].

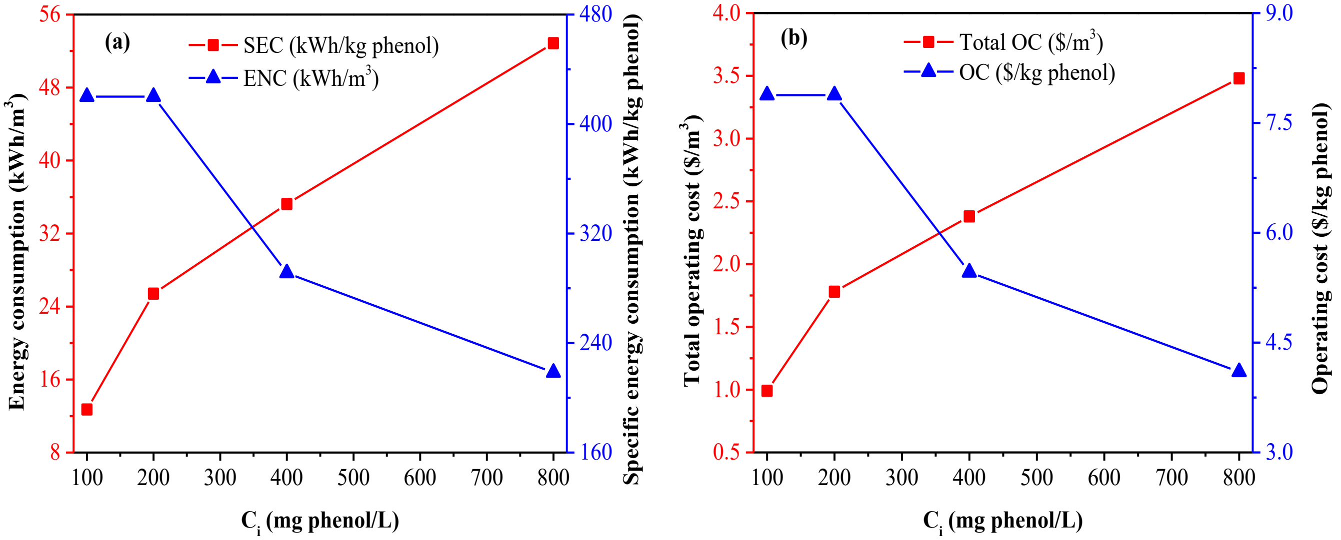


Figure 7. *Impact of initial phenol concentration on (a) specific energy consumption and (b) total operating costs.*

As can be seen from (Figure. 8), under optimum conditions (anode = BDD, j = 200 A/m^2, and initial pH= 7.60) for 2, 4 and 6 gNaCl/L supported electrolytes, the residual phenol concentration for 2 gNaCl/L was 0.001 mg/L after 60 min, however, for 4 and 6 gNaCl/L it was 0.001 mg/L after 50 min, indicating that the increase from 4 to 6 gNaCl/L supported electrolyte has no migratory effect on phenol removal. Similar results were obtained by Zambrano et al. (2019), where treatment with 6 g NaCl/L led to slightly higher removal than treatment with 8 g NaCl/L. As can be seen from the results, the higher concentration of the supported electrolyte, the higher removal of phenol, which may be due to the fact that at low NaCl concentrations, there is a smaller amount of Cl^- ions available to promote the formation of oxidants. However, the electrochemical process using higher electrolyte concentrations quickly reaches alkaline pH, favoring the production of ClO^- species [51]. These species also promote the slowing down of phenol oxidation. In a study by Zambrano and Min (2019), two different supporting electrolytes (NaCl and Na_2SO_4) were used as Pt/Ti anode for the removal of 100 mg/L phenol at a current density of 96 A/m^2. In this study, it was found that the EO time required for 98.21 ± 3.10% phenol removal was 180 mins when 10 gNaCl/L was used as the supporting electrolyte, but complete phenol removal was achieved after 600 mins when 10 gNa_2SO_4/L was used as the supporting electrolyte. Complete and faster phenol removal was observed when NaCl was used as a supporting electrolyte compared to working with Na_2SO_4 as the electrolyte, probably due to the successful production of active chlorine [52].

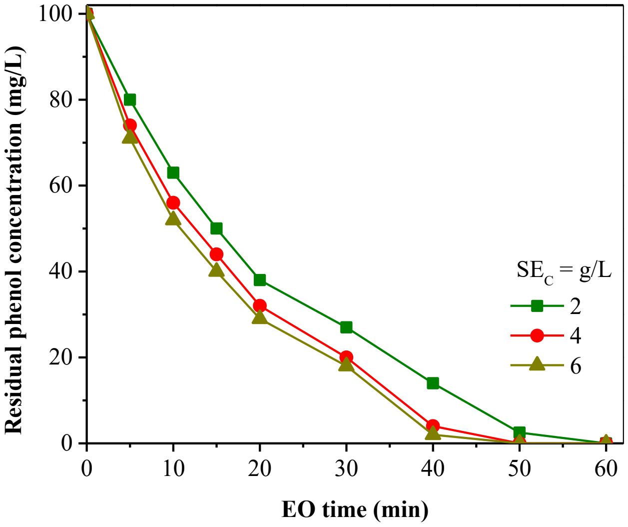


Figure 8. *Impact of supporting electrolyte concentrations on phenol removal efficiency.*

As can be seen from (Figure. 9), the SEC and total OC required under the optimum conditions of the study (anode = BDD, j = 200 A/m^2, pH = 7.60) for different supported electrolyte concentrations were calculated as 18.8 kWh/m^3 (600.0 kWh/kg phenol) and 1.23 \$/m^3 (11.25 \$/kg phenol) for 2 gNaCl/L, 12.7 kWh/m^3 (420.0 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol), and 11.6 kWh/m^3 (384.0 kWh/kg phenol) and 1.02 \$/m^3 (7.20 \$/kg phenol) for 6 gNaCl/L, respectively. As can be seen from the results, the lowest SEC and total OC were obtained for the high supported electrolyte concentration of the study.

This is because the cell voltage drop leads to low energy consumption, resulting in low operating costs for the study. However, the use of high amounts of supported electrolytes also results in high operating costs, as can be seen in (Figure. 9 b), where the use of 6 gNaCl/L supported electrolyte resulted in higher operating costs than the use of 4 gNaCl/L supported electrolyte. Although it causes the cell voltage to drop, the cost of conduction is higher. This can be explained by the use of excess chemicals.

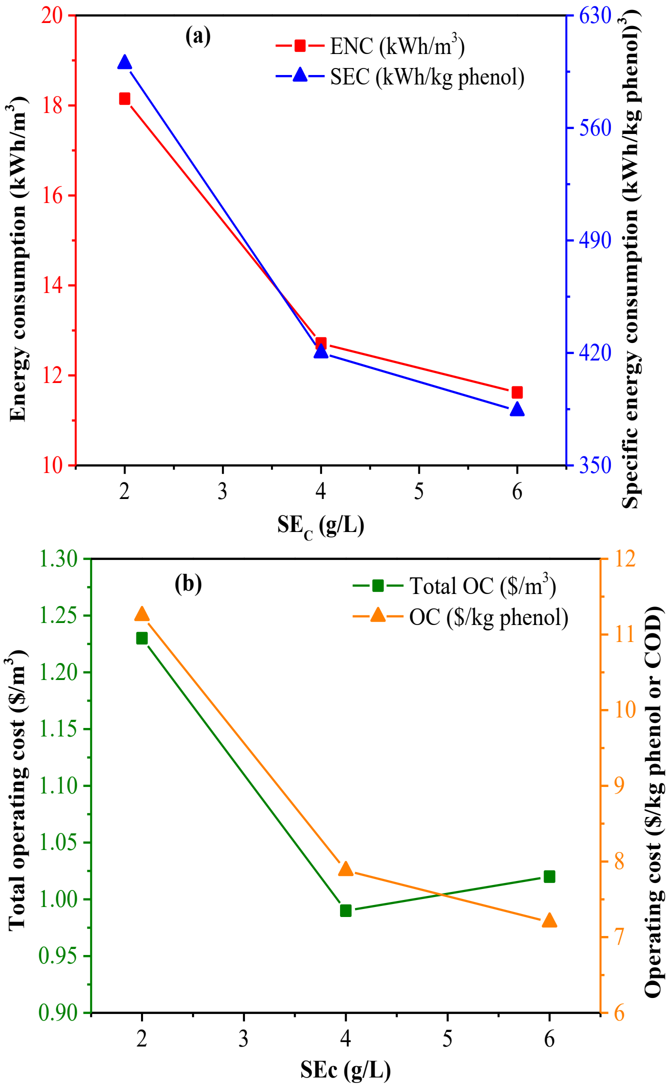


Figure 9. *Impact of supporting electrolyte concentration on (a) specific energy consumption and (b) total operating costs.*

3.5. Comparison of different conventional processes for phenol removal

Different studies on phenol oxidation, energy consumption, and total operating cost analysis have been carried out in the existing literature (as shown in Table. 1), for instance, Gümüş and Akbal (2016) calculated 81.1% for 250 mg/L phenol removal in the classical Fenton process with a starting pH of 10, H_2O_2 concentration of 500 mg/L, and Fe^{2+} dosage of 15 mg/L. However, the OC for this condition was 1.337 \$/kg-phenol. In the same study, Gümüş and Akbal (2016) calculated 93.3% for the electro-Fenton process for 250 mg/L phenol removal with an initial pH of 3, applied current of 0.9 A, and Fe^{2+} dosage of 15.2 mg/L. On the other hand, the OC for this condition was 1.003 \$/kg-phenol [53]. In another study, Amado-Piña et al., (2017) applied sequential ozone/EO process for 100 mg/L phenol removal, the optimum conditions were calculated as 100% phenol oxidation with initial pH value 7, BDD/SS as anode and cathode, applied current density 600 A/m^2, EO process oxidation time 180 min, wastewater flow rate 0.05 mL/min, SEc concentration 0.1 M Na_2SO_4/L, and O_3 concentration 5 mg/L [54]. In our study, the EO process was applied for phenol oxidation of 100% under optimum conditions (initial concentration of 100 mg phenol/L, initial pH of 7.6, BDD/SS as anode and cathode, applied current density 200 A/m^2, and EO process oxidation time 50 min, SEc of 4 g NaCl/L). However, ENC and total OC for the study were calculated as 12.7 kWh/m^3 (420 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol), respectively.

Table 1. An overview of literature studies on phenol removal by different conventional processes.

Treatment process	Optimum values	R_e (%)	Energy consumption and total OC	References
Fenton	pH = 10, C_i = 250 mg/L, H_2O_2 concentration = 500 mg/L, Fe^{2+} dose = 15 mg/L	81.1	OC = 1.337 \$/kg-phenol	[53]
Electro-Fenton	pH = 3, anode/cathode = Fe/Fe, C_i = 250 mg/L, j = 0.9 A, t = 5 min, Fe^{2+} dose = 15.2 mg/L, SEc = 1 g Na_2SO_4/L	93.3	OC = 1.003 \$/kg-phenol	
Electro-Fenton	pH = 3, anode/cathode = nickel/carbon felt, C_i = 100 mg/L, j = 0.9 A, t = 90 min, Fe^{2+} dose = 20 mg/L	95.2	-	[55]
O_3-EO	pH = 7, anode/cathode = BDD/SS, C_i = 100 mg/L, j = 600 A/m^2, t = 180 min, Q = 0.05 mL/min, O_3 = 5 mg/L, SEc = 0.1 M Na_2SO_4/L	100	-	[54]
EO	pH = 3.4, anode/cathode = graphite /graphite, C_i = 500 mg/L, j = 150 A/m^2, t = 120 min	59.4	C_{energy} = 111 kWh/kg-phenol	[56]
EO	pH = 3.4, anode/cathode = Ti/RuO_2/SS, C_i = 323 mg/L, j = 1190 A/m^2, t = 180 min, SEc = 10 g NaCl/L	97.2	C_{energy} = 162 kWh/m^3	[57]
EO	pH = 5, anode/cathode = Pt/Ti, C_i = 90 mg/L, j = 91 A/m^2, t = 1440 min	99.9	C_{energy} = 14 kWh/m^3	[58]
EO	pH = 7.6, anode/cathode = BDD/SS, C_i = 100 mg/L, j = 200 A/m^2, t = 50 min, SEc = 4 g NaCl/L	100	C_{energy} = 12.7 kWh/m^3 (420 kWh/kg-phenol), OC = 0.99 \$/m^3 (7.88 \$/kg-phenol)	**Present work**

4. Conclusion

In this study, the removal of phenol from an aqueous solution using a BDD anode in the EO process was investigated. Different current densities, initial pH, phenol concentrations, and supported electrolyte concentrations were investigated. As the current density increased, the rate of phenol oxidation also increased. The most efficient results were obtained at a current density of 200 A/m^2 and the initial pH of the aqueous solution (7.60). In this study, although the supported electrolyte helped to reduce the cell voltage in the study, it was found that the removal efficiency did not have a high effect when using the supported electrolyte at a concentration higher than 4 g NaCl/L. Under these conditions, 100 mg/L phenol oxidation was 100% in 50 min. The SEC and total OC required for the removal of 100 mg/L phenol concentration under optimum conditions (anode = BDD, j = 200 A/m^2, pH = 7.60, SE_c = 4 gNaCl/L) were calculated as 12.7 kWh/m^3 (420 kWh/kg phenol) and 0.99 \$/m^3 (7.88 \$/kg phenol), respectively. The findings of the study show that the EO process using a BDD anode is a very efficient choice for phenol oxidation from an aqueous solution. The use of EO methods offers several advantages, such as user-friendly equipment, reduced treatment time, and economical costs of phenol oxidation.

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