

Performance of electrochemical oxidation over BDD anode for the treatment of different industrial dye-containing wastewater effluents

Arwa Abdelhay, Inshad Jum'h, Abeer Albsoul, Dina Abu Arideh and Bahaa Qatanani

ABSTRACT

This paper presents the results of electrochemical oxidation of dye-containing wastewater over a BDD anode. Batch experiments were conducted at a fixed current density of 2.8 mA/cm² to analyze the performance of the electrochemical process for the treatment of textile and paint wastewater utilizing different supporting electrolytes (Na₂SO₄ and NaCl). During electrolysis, emphasis was put on measuring different parameters such as chemical oxygen demand (COD), turbidity, conductivity, and color removal. The results revealed that BDD cell exhibited higher COD removal efficiency for textile wastewater than for paint wastewater. Adding supporting electrolytes had a positive effect on COD, turbidity, and color removal efficiencies for both textile and paint industry effluents. For textile wastewater, Na₂SO₄ and NaCl yielded a reduction in COD of 94% in 6 hours compared to 84% with no electrolyte added. The presence of Na₂SO₄ and NaCl in paint wastewater resulted in different COD removal percentages of 71 and 85% respectively with 21% in raw sample after 4 hours of treatment. The discoloration reached a percentage higher than 96% for both effluents and for both electrolytes. Under the same experimental conditions, all cases showed turbidity removal higher than 97%. The kinetic study showed that the reaction rate followed pseudo-first-order kinetics.

Key words | BDD anode, electrolysis, paint wastewater, supporting electrolytes, textile wastewater

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HIGHLIGHTS

- This paper introduced the idea of using electrochemical oxidation as an AOP to treat real industrial WW effluents and to remove dye in particular.
- Efficient application of BDD anodic oxidation for the treatment of textile and paint wastewater.
- A comparison of the performance of the electrochemical cell was carried out for textile and paint wastewater.
- The performance of the EC cell was enhanced by utilizing chloride and sulfate electrolytes (NaCl and Na₂SO₄) have been made.

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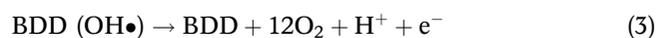
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INTRODUCTION

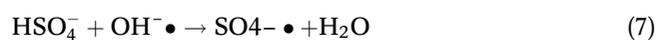
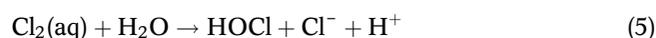
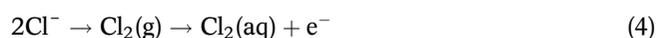
Rapid industrialization and growing water demand due to dramatic population growth are key drivers to adopt the integrated water resources management (IWRM) approach. Wastewater treatment and reuse is one of the key pillars of the IWRM and has great potential to increase the unconventional water resources share in the water budget. Several industries produce substantial volumes of wastewater effluents. Therefore, the control and treatment of industrial wastewater is of vital importance since reclaimed wastewater can be reused for several purposes. Thus, wastewater reuse seems to be the most obvious way of dealing with water scarcity. However, these effluents contain a variety of recalcitrant contaminants that cannot be handled by conventional treatment and require costly physical or physico-chemical pretreatments (Körbahti & Tanyolaç 2009). This fact, along with the stringent water quality requirements and the strict directives, triggered a search for innovative non-conventional treatment methods. The treatment methods include several techniques such as membrane technology (Obotey Ezugbe & Rathilal 2020), UV/ozonation radiation (Jacqueline & Renato 2019; Malvestiti *et al.* 2019), Fenton oxidation (Ebrahiem *et al.* 2017), photocatalytic degradation (Zhang *et al.* 2014), and phytoremediation (Hegazy *et al.* 2011). Among the various tested and proposed methods in literature, advanced oxidation processes (AOPs) were adopted as performant technologies to remove hardly degradable organics. Miklos *et al.* (2018), divided the AOP processes into five main categories, namely ozone based, UV based, electrochemical AOP, catalytic AOP, and physical AOP. In particular, electrochemical oxidation and photocatalysis have attracted the attention of researchers worldwide as AOP treatment processes. However, interest was growing more toward electrochemical methods due to their competitive capacity to destruct persistent and recalcitrant organics, cost effectiveness, versatility, and short treatment time (Radha *et al.* 2009; Dheeravath *et al.* 2018). Moreover, Escudero *et al.* (2017) showed that the electro-chemical oxidation had an energy consumption 8-fold smaller than photocatalysis, and higher kinetic constants, which made it more attractive for scaling up purposes. The degradation of organics through electrochemical oxidation is guaranteed

by indirect and/or direct anodic reactions in which an electron transfer takes place between water and the organic compound to be oxidized (Martínez-Huitile & Brillas 2009). Direct anodic oxidation involves the adsorption of pollutants on the surface of the anode, where electron transfer reaction or the generation of highly reactive free radicals (OH[•]) result in their degradation (Sánchez-Sánchez *et al.* 2018).

The degradation mechanism of recalcitrant organics over BDD electrodes by direct oxidation was explained by previous research studies and they indicated that the oxidation of organics and oxygen evolution take place on a BDD anode surface via the intermediation of hydroxyl radicals generated from the reaction as shown in the following reactions (Linares-Hernández *et al.* 2010):



Indirect anodic oxidation is mediated by electrogenerated oxidants such as hypochlorite, chlorine, ozone, or hydrogen peroxide near the anode surface or in the bulk electrolyte (Martínez-Huitile *et al.* 2015) according to the following chemical reactions:



The efficiency of the electrochemical process is a function of several parameters and most important are the electrode material, the electrolyte type, and the characteristics of the treated wastewater. Recently, the application of conductive BDD anode in the degradation of wastewater pollutants has received great attention because of several

technologically important characteristics of BDD anode including high O₂ evolution overvoltage, an inert surface with low adsorption properties, and remarkable corrosion stability (Fan *et al.* 2016; Zou *et al.* 2017). Moreover, many researchers tested the performance of BDD electrochemical oxidation for different types of wastewater (Abdelhay *et al.* 2017, 2019; Jum'h *et al.* 2017a; Migliorini *et al.* 2016; Cabral da Silva *et al.* 2013).

The goal of the current work is to investigate the electrochemical treatment of wastewater in a BDD based electrochemical cell and in the presence of different types of electrolytes. The cell was utilized to treat two different industrial wastewaters, namely textile and paint which were used as models for dye-containing wastewater. To our knowledge, no work has been carried out to test the performance of the same electrochemical setup design to treat two wastewater types representing dye-containing wastewater such as textile and paint effluents.

MATERIALS AND METHODS

Textile and paint wastewater samples

Textile wastewater samples used in this work were collected after the dyeing process in the textile industry in Sahab industrial City, Jordan. Paint wastewater samples were provided by a paint manufacturing company (National) in Jordan. The samples were transported in sealed plastic containers and refrigerated at 4 °C. It should be noted that the collected samples did not receive any chemical or physical treatment prior to the electrochemical oxidation. The characteristics of the wastewater samples obtained from both the textile and paint industry and used in the current study are summarized in Table 1.

Table 1 | Characteristics of raw water collected from textile and paint industry

Characteristics	Value (textile WW)	Value (paint WW)
Color	Light blue	White opaque
pH	5.4	5.9
Turbidity (NTU)	369	773
Total suspended solids (mg/L)	560	870
COD (mg/L)	1,650	550
Conductivity (mS/cm)	4.43	1.04

Experimental setup and procedure

The experimental runs were performed in a batch laboratory-scale electrochemical square reactor made of Plexiglas with 5 L capacity, as shown in Figure 1. The reactor was equipped with two plate BDD electrodes, one serving as anode and the other one as cathode. Each plate has an effective area of 196 cm² (14 × 14 cm), a thickness of 2.8 mm and the spacing between the two plate electrodes was 1 mm. The BDD electrodes were prepared in the laboratory by implementing the hot filament chemical vapor deposition coating method (Coating machine CC800/8 DIA). The electrodes were niobium substrate based (Figure 2). The niobium grid was coated on both sides using two parallel filament rows for 50 h. The surfaces of the electrodes were properly cleaned from impurities before each experiment using an ultrasonication bath. A standard DC power supply (Gwisntek GPC 30300) was used as the source of electric current for the experiments. The DC supply provided the system with a working current and voltage of 2.5 A and 3 V respectively. All batch runs were conducted at 25 °C and 2.8 mA/cm² with a working volume of 0.5 L. The characterization of the treated wastewater was performed by withdrawing a sample every 15 min in sealed and clean 20 mL glass vials in order to analyze them

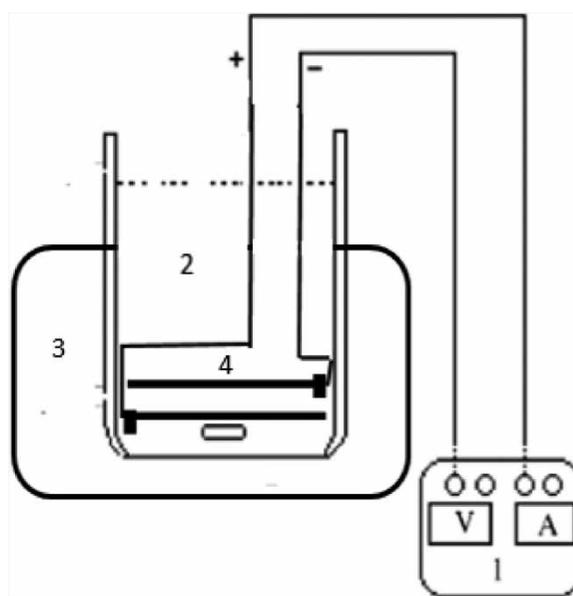


Figure 1 | Schematic diagram of experimental setup: (1) DC power supply; (2) electrochemical cell; (3) water bath; (4) BDD electrodes.

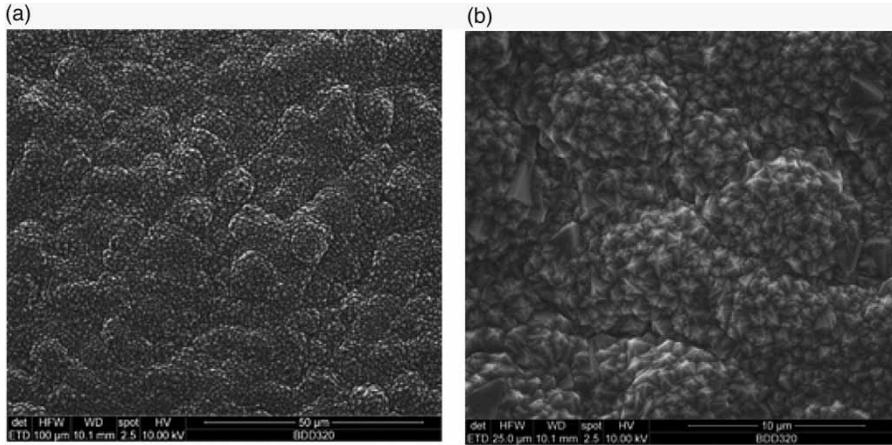


Figure 2 | (a,b) Scanning electron microscopy (SEM) image of the BDD layers deposited on niobium substrate in two different magnifications (Jum'h et al. 2017b).

afterwards. In the current work, the performance of the electrochemical BDD cell to treat both textile and paint wastewater effluents was evaluated in terms of chemical oxygen demand (COD) removal, turbidity removal, color removal, and energy consumption. The performance was also followed up in the presence of different supporting electrolytes (Na_2SO_4 and NaCl).

Analytical procedure

The investigated variables (COD, turbidity, and color) were recorded for 4 and 6 hours of electrolysis for paint and textile wastewater respectively. The COD values of the initial and treated samples were determined as per those detailed in the standard methods (APHA 1992). The COD readings of the electrolyzed samples were measured using a Hach digester (DRB 200-Germany) and Hach spectrophotometer (DR/2010-Germany). The turbidity of the samples was measured with a Wagtech turbidity meter. The discoloration throughout the electrolysis time was quantified based on the absorbance, which was measured at a band of 450 nm with a Wagtech 7100 photometer. The color removal was calculated using the following equation:

$$\%color\ removal = \frac{ABS(initial) - ABS(t)}{ABS(initial)} * 100\% \quad (9)$$

where ABS (initial): is the initial absorbance of the raw sample, ABS (t): is the absorbance of the treated sample at regular time intervals, t .

The pH and conductivity of the collected samples were measured using a digital calibrated Jenway 3,540 pH/conductivity meter.

Sodium sulfate Na_2SO_4 and NaCl (Sigma Aldrich) were used as supporting electrolytes with a concentration of 1 g/L.

Energy consumption estimation

The estimation of the energy consumption for electrochemical treatment processes is a major concern when scaling up is accounted for. Thus, the specific energy consumption E_{sc} using each supporting electrolyte was calculated in kWh consumed per kg COD removed according to the following equation:

$$E_{sc} = \frac{A * V * t}{\Delta} COD \quad (10)$$

where t is the time of electrolysis (h); V and A are the average cell voltage and the electrolysis current; v is the sample volume (L), and ΔCOD is the difference in COD between initial and final readings in (mg/L).

Kinetic study

A kinetic analysis was carried out to check the validity of the pseudo first-order equation in describing the COD evolution throughout the electrolysis time in the presence of different electrolytes. The rate constant calculated from the pseudo

first-order equation was used as a tool to compare the electrochemical kinetics of COD removal from textile and paint wastewater when different supporting electrolytes were used. The pseudo first-order kinetic can be represented by the following equation:

$$COD = COD_0 * e^{-kt} \quad (11)$$

where COD_0 is the initial chemical oxygen demand at the beginning of the electrolysis process (mg/L), COD is the chemical oxygen demand at time t (mg/L), k is the electrolysis rate constant (t^{-1}), and t is the time of electrolysis.

RESULTS AND DISCUSSION

Effect of supporting electrolytes on COD removal

In this part, the performance of the BDD electrochemical cell was first evaluated by analyzing the COD removal utilizing different electrolytes. Specifically, electrolysis was conducted using different types of supporting electrolytes (Na_2SO_4 and $NaCl$) to investigate their effect on the COD removal efficiency. The COD removal efficiency has been plotted versus the electrolysis time in Figure 3 for textile industry wastewater. It can be clearly noticed from Figure 3

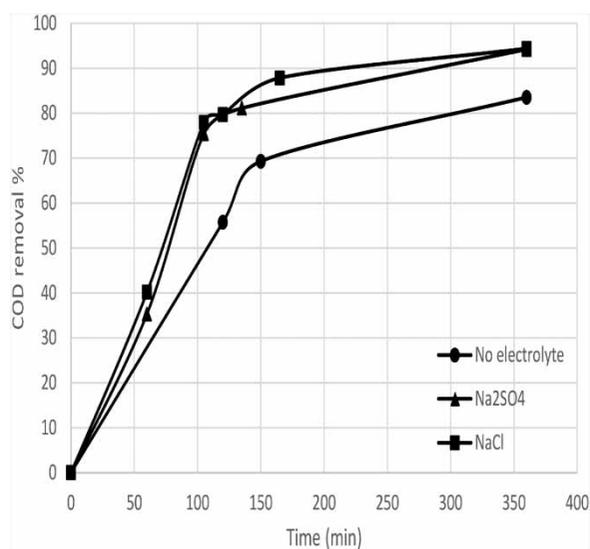


Figure 3 | Effect of adding electrolyte to textile wastewater on COD removal (2.8 mA/cm², 25 °C, 1 g/L Na_2SO_4 , 1 g/L $NaCl$, pH = 5.4).

that adding supporting electrolytes led to an improvement in the COD removal. Figure 3 depicts that a COD removal of 94% was achieved after 6 hours of treatment using both $NaCl$ and Na_2SO_4 as supporting electrolytes. Similar results were observed by De Almeida *et al.* (2014) where a COD removal of 95% was obtained before 10 hours of electrolysis for $NaCl$ and Na_2SO_4 . On the other hand, the COD removal obtained in the raw sample was about 84%, which is 11% less than the removal with supporting electrolytes. Uranga-Flores *et al.* (2015) confirmed that Na_2SO_4 influences COD degradation by two mechanisms of generation of oxidative species, namely a direct oxidation in the anode, including SO_4^- and HSO_4^- or by $S_2O_8^-$ generated from the reaction of hydroxyl radicals with the electrolyte. Thus, it can be hypothesized that the reasons for COD removal improvement are either the electro-generation of peroxydisulfate ($S_2O_8^-$) and hypochlorite/chlorine ($HOCl/ClO^-$) free radicals or the increase in the conductivity of the solution, which would result in higher cell performance (De Almeida *et al.* 2014). In an attempt to test the later hypothesis, the conductivity of the sample was measured throughout the electrolysis time with and without supporting electrolytes (Figure 4). As can be seen in Figure 4, the conductivity of chloride and sulfate containing solutions was higher than the one of the raw sample until an electrolysis time of 200 min. This observation confirmed that the increase in conductivity could justify the positive effect of adding supporting electrolytes on COD removal. Moreover, it coincides with the results of Sánchez-Sánchez *et al.* (2018)

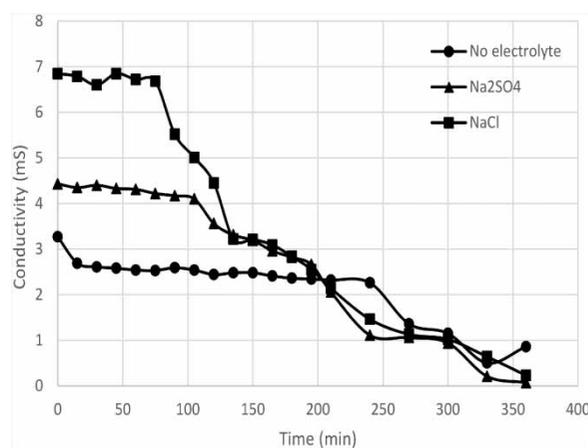


Figure 4 | Effect of adding electrolyte to textile wastewater on conductivity (2.8 mA/cm², 25 °C, 1 g/L Na_2SO_4 , 1 g/L $NaCl$, pH = 5.4).

where higher conductivity was justified by a mineralization in the electrochemical oxidation process.

However, the superior conductivity values in samples containing electrolytes diminished after 200 min of electrolysis. Nonetheless, the COD removal values with electrolytes were still higher after 200 min compared to raw samples with no electrolyte added. Therefore, it can be suggested that the electro-generation of peroxydisulfate and hypochlorite/chlorine free radicals was a second mechanism also contributing to the improvement in the COD removal efficiency. This conclusion can be supported by the findings of *Aquino et al. (2012)* who proved that in the presence of chloride ions, the primary mechanism for dye oxidation is mediated electro-oxidation. The maximum COD removal reported in the current section for NaCl sample (94%) where the electrolyte concentration was 1 g/L and the current density was 2.8 mA/cm^2 is higher than the value obtained by *Babu et al. (2012)*, which was 80% using almost the same electrolyte concentration and current density.

The performance of the electrochemical cell was also tested using paint industry wastewater. In this case, the positive effect of carrying out the electrolysis with supporting electrolytes was clear as well (*Figure 5*). The results showed that a higher COD removal was observed with NaCl than with Na_2SO_4 . The COD removal increased from 22 to 71% and from 22 to 85% after 4 hours of treatment using Na_2SO_4 and NaCl respectively. By analogy to the previous part, a conductivity test was conducted (*Figure 6*). The results revealed that the conductivity values were almost constant over the electrolysis time for

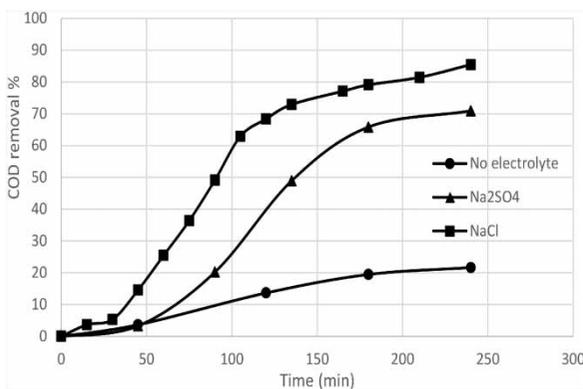


Figure 5 | Effect of adding electrolyte to paint wastewater on COD removal (2.8 mA/cm^2 , 25°C , $1 \text{ g/L Na}_2\text{SO}_4$, 1 g/L NaCl , $\text{pH} = 5.9$).

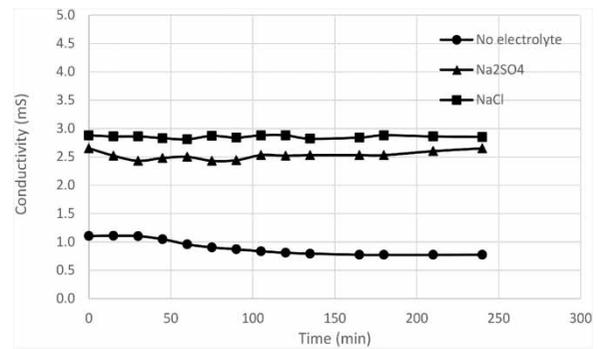


Figure 6 | Effect of adding electrolyte to paint wastewater on conductivity (2.8 mA/cm^2 , 25°C , $1 \text{ g/L Na}_2\text{SO}_4$, 1 g/L NaCl , $\text{pH} = 5.9$).

the three tested samples. The conductivity results for paint wastewater were in accordance with the COD removal trend as the highest conductivity was in descending order for NaCl, Na_2SO_4 , and raw sample. As previously mentioned, it can be concluded that raising the conductivity is a reason for enhancing the mineralization and thus the COD removal efficiency in wastewater samples (*Körbahti et al. 2007*).

Of particular interest, the optimal COD removal in textile wastewater was 94%, with 85% in paint wastewater. Both of these optimal values were achieved with NaCl as supporting electrolyte. It is worth mentioning that although paint wastewater is less polluted than textile wastewater, as manifest by the lower COD concentration (550 mg/L), the electrochemical cell was less efficient in COD removal from raw paint wastewater (22%) than from textile wastewater (84%). This performance gap is most likely due to the difference in conductivity values between paint and textile wastewater, either in the presence or absence of supporting electrolytes, with textile water having higher conductivity values. It has been reported that textile wastewaters originally contain a variety of inorganic ions that are responsible for the formation of strong secondary oxidants, such as active chlorine and peroxidisulfate (*Zou et al. 2017*).

Effect of supporting electrolytes on turbidity removal

Supporting electrolytes are key elements during electro-oxidation of wastewater as they increase the electrolyte conductivity and hence decrease the energy consumption of the electrochemical cell. In this regard, the effect of

adding two supporting electrolytes (Na_2SO_4 and NaCl) on the turbidity removal by electrochemical oxidation of two types of wastewater was investigated. The turbidity profile was plotted versus the electrolysis time for textile (Figure 7) and paint (Figure 8) wastewater. It can be observed that for all wastewater samples tested in Figures 7 and 8, the turbidity removal increased with the electrolysis time (Pekel et al. 2013). This could be attributed to the increase in the electro-generated free radicals that would oxidize the insoluble complex organics and result in their solubilization throughout the oxidation process. The results reported in Figure 7 revealed that the electrochemical oxidation of textile wastewater was favored during the first 4 hours by the higher removal kinetics in textile samples containing Na_2SO_4 and NaCl . This may be justified by an increase in the rate of electro-generation of peroxydisulfate and hypochlorite/chlorine

free radicals from Na_2SO_4 and NaCl respectively (Mohan et al. 2007). The peroxydisulfate and hypochlorite/chlorine are considered secondary powerful oxidants that could expedite the electro-oxidation of organics by (OH^\cdot) free radicals through a supplementary mediated oxidation. However, the ultimate turbidity removal efficiency in raw wastewater after 6 hours of treatment was the same value (97%) as in textile samples containing Na_2SO_4 and NaCl .

For paint wastewater samples, a similar trend was observed in Figure 8 where the turbidity removal increased with the electrolysis time. K rbahti & Tanyola  (2009) reported that during electrochemical treatment, organic molecules were electro-oxidized at the anode or electro-reduced at the cathode forming smaller intermediate molecules. The concentration of the aforementioned molecules decreased with time. However, in this case the highest turbidity removal efficiency (97.5%) was obtained when NaCl was added as a supporting electrolyte (Brillas & Mart nez-Huitle 2015; Abdelhay et al. 2017). The Na_2SO_4 had an adverse effect on the turbidity removal, which is manifest by lower turbidity removal values in the first 2 hours than those reported for the raw sample.

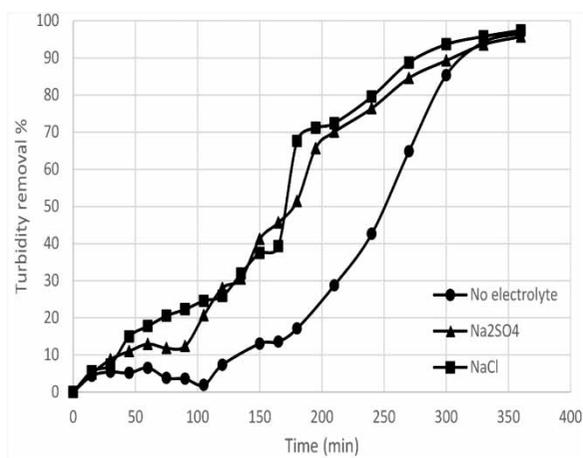


Figure 7 | Effect of adding electrolyte to textile wastewater on turbidity removal (2.8 mA/cm², 25 °C, 1 g/L Na_2SO_4 , 1 g/L NaCl , pH = 5.4).

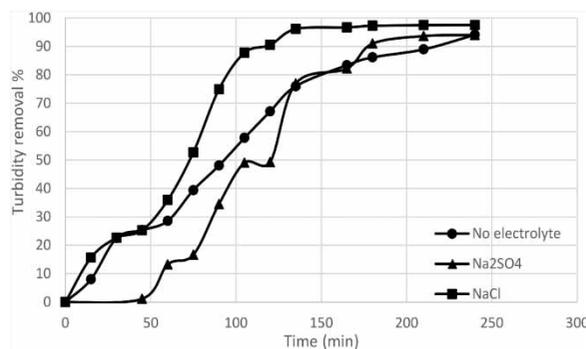


Figure 8 | Effect of adding electrolyte to paint wastewater on turbidity removal (2.8 mA/cm², 25 °C, 1 g/L Na_2SO_4 , 1 g/L NaCl , pH = 5.9).

Effect of adding supporting electrolytes on color removal as a function of electrolysis time

Color removal is of great interest, especially in the case of textile wastewater due to the presence of dyes. Experiments were conducted to follow up the disappearance of the blue color from textile wastewater electrochemically treated for 6 hours using different supporting electrolytes. Figure 9

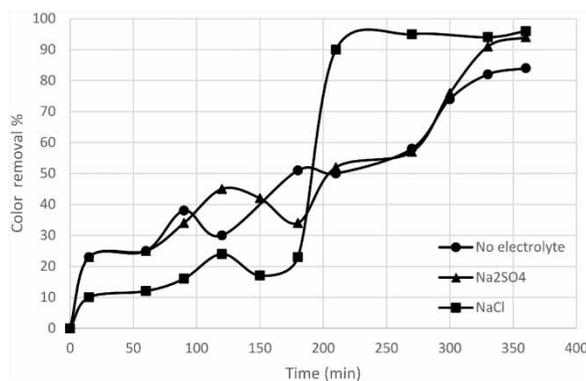


Figure 9 | Effect of adding electrolyte to textile wastewater on color removal (2.8 mA/cm², 25 °C, 1 g/L Na_2SO_4 , 1 g/L NaCl , pH = 5.4).

illustrates the color removal percentage (absorbance reduction) during the electrolysis time when Na_2SO_4 and NaCl were added. The results suggested that the color removal percentage increased with increasing the electrolysis time. A maximum color removal of 96% was achieved after 6 hours of treatment in samples containing NaCl or Na_2SO_4 . However, a lower color removal (84%) was attained in the raw sample treated for 6 hours. These results are in accordance with the COD removal trend presented in Figure 3. It should also be noted that the color removal rate in samples containing NaCl increased dramatically after a treatment time of 200 min. The higher efficiency of electrochemical cells operating with NaCl in color removal from textile wastewater is attributed to the active participation of electrogenerated chlorine oxidants in dye degradation (Aquino et al. 2011; Kariyajjanavar et al. 2011). Indirect oxidation withstands the direct oxidation by hydroxyl free radicals and shortens the treatment time (Aquino et al. 2012).

Figure 10 shows the discoloration of the textile sample after 6 hours of electrolysis with NaCl as supporting electrolyte. It can be observed that the blue color disappeared completely in the treated sample. This observation confirmed the results reported in Figure 9 where 96% of the color was removed when the sample was treated for 6 hours using NaCl as supporting electrolyte.



Figure 10 | Discoloration of textile wastewater after 6 hours of electrolysis with BDD anode using NaCl as supporting electrolyte (2.8 mA/cm^2 , 25°C , $1 \text{ g/L Na}_2\text{SO}_4$, 1 g/L NaCl , $\text{pH} = 5.4$).

The efficiency of the cell was also tested for paint wastewater treatment using electrochemical oxidation on BDD by following up the discoloration during the electrolysis time (Figure 11). The results suggested that the color removal percentage increased notably throughout the electrolysis time. Conversely to textile wastewater, the color removal percentage recorded for paint wastewater after 4 hours was slightly different for raw samples, NaCl , and Na_2SO_4 . The color removal was 95, 98, and 100% for raw samples, NaCl , and Na_2SO_4 respectively. A possible justification of this observation is that the color-causing organics were degraded by hydroxyl free radicals during electrolysis. Other organics were possibly oxidized by the mediated oxidation supported by the electro-generated chlorine/hypochlorite or peroxydisulfate oxidants as was suggested by the COD results presented previously in Figure 5.

Kinetic study of COD oxidation

The COD results of anodic electrolysis of textile wastewater in the presence of different supporting electrolytes were subjected to kinetic equation analysis. The results revealed that the COD abatement obtained throughout the 6 hours of electrolysis was well presented by a pseudo first-order model fitting (Figure 12) with a correlation coefficient higher than 0.85 for the three cases. The pseudo first-order rate constants were 0.0054 , 0.0088 , and 0.0095 min^{-1} for raw sample, Na_2SO_4 , and NaCl respectively. The rate constant values are in agreement with the COD removal results where the highest values were obtained when Na_2SO_4 and NaCl had been added to the raw sample.

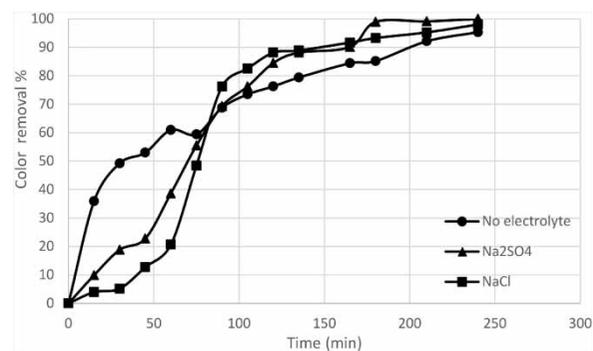


Figure 11 | Effect of adding electrolyte to paint wastewater on color removal (2.8 mA/cm^2 , 25°C , $1 \text{ g/L Na}_2\text{SO}_4$, 1 g/L NaCl , $\text{pH} = 5.9$).

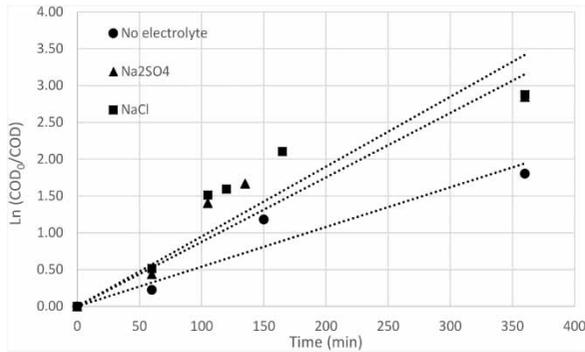


Figure 12 | Kinetic analysis of textile wastewater electrolysis with BDD anode using different supporting electrolyte (2.8 mA/cm², 25 °C, 1 g/L Na₂SO₄, 1 g/L NaCl, pH = 5.4).

The pseudo first-order model was also valid in representing the COD variation during the electrolysis of paint wastewater using different supporting electrolytes (Figure 13). A good correlation was observed between the predicted data by the pseudo first-order equation and the COD experimental results as manifest by a correlation

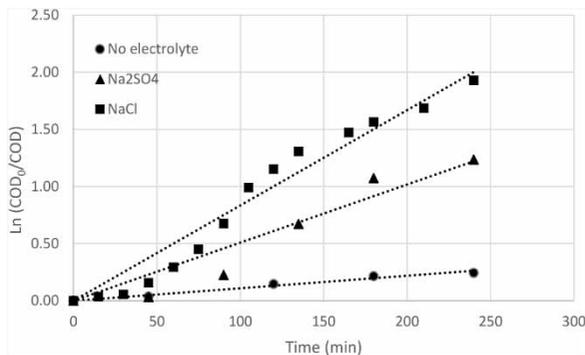


Figure 13 | Kinetic analysis of paint wastewater electrolysis with BDD anode using different supporting electrolyte (2.8 mA/cm², 25 °C, 1 g/L Na₂SO₄, 1 g/L NaCl, pH = 5.9).

Table 2 | Values of first-order rate constant reported in literature and in the current study

Wastewater type	Supporting electrolyte	Concentration of supporting electrolyte (g/L)	J (mA/cm ²)	k	Reference
Textile	NaCl	1	2.8	9.5×10^{-3}	Current work
	NaCl	1	60	7.06×10^{-3}	Zou <i>et al.</i> (2017)
	Na ₂ SO ₄	1	2.8	8.8×10^{-3}	Current work
	Na ₂ SO ₄	4	7.5	5.75×10^{-4}	Escudero <i>et al.</i> (2017)
	No electrolyte	0	5	0.135	Radha <i>et al.</i> (2009)
Paint	NaCl	1	2.8	8.3×10^{-3}	Current work
	NaCl	1	20	4.385×10^{-2}	Yao <i>et al.</i> (2019)
	Na ₂ SO ₄	1	2.8	5.1×10^{-3}	Current work

factor exceeding 0.92. The modeled rate constants were 0.0011, 0.0051, and 0.0083 min⁻¹ for raw sample, Na₂SO₄, and NaCl respectively. Interestingly, the rate constants followed the same trend as that observed for COD removal using different supporting electrolytes, which confirms the validity of the pseudo first-order kinetics. According to Zou *et al.* (2017) the more contribution of indirect oxidation mediated by the strong oxidants to the COD oxidation, the higher the obtained pseudo-first-order kinetic constant k, meaning faster oxidation kinetics. Table 2 shows a comparison of kinetic constants obtained in the current work with values reported in literature. It is worth noting that Table 2 illustrates the different kinetic constants, however a comparison cannot be carried out as the working conditions among the different studies were different.

Energy consumption

The appropriate selection of supporting electrolyte is an important factor in reducing the energy consumption, which directly affects the viability of the wastewater treatment process. Regarding the influence of supporting electrolytes on the specific energy consumption, as shown in Table 3, adding electrolytes to the treated samples

Table 3 | Esc for COD oxidation using different supporting electrolytes

Wastewater	Supporting electrolyte	Esc (KWh/kg COD)
Textile	None	65.31
	Na ₂ SO ₄	57.91
	NaCl	57.80
Paint	None	504.20
	Na ₂ SO ₄	153.84
	NaCl	127.65

resulted in lower E_{sc} , from 65.31 kWh/kg COD for the raw sample to 57.80 kWh/kg COD for the case of NaCl when textile wastewater was treated. A similar trend was observed for the treated paint wastewater as the E_{sc} dropped from 504.20 kWh/kg COD (raw sample) to 127.65 kWh/kg COD (NaCl). Increasing NaCl concentrations can improve the conductivity of wastewaters and thus reduce the E_{cell} (Zou et al. 2017). A second probable reason for this behavior is that using NaCl as supporting electrolyte could lead to faster oxidation kinetics and could obtain higher current efficiency through secondary reactions with the participation of active chlorines (Zou et al. 2017). However, it is worth noting that the E_{sc} values calculated for paint wastewater were much higher than textile wastewater, which could be due to higher conductivities in the case of textile wastewater regardless of the type of supporting electrolyte. It is hard to compare the E_{sc} values of the current study with what has been reported in the literature because of the difference in operating conditions. Few examples on similar work, Tsantaki et al. (2012) could reach a COD removal of 80% after an electrolysis time of 3 hours and an applied current density of 8 mA/cm², and the energy consumption was around 75 kWh/kg COD. Solano et al. (2013) reported an energy consumption of 36.96 kWh/m³ when textile wastewater was electro-oxidized for 10 hours using a current density of 40 mA/cm². Regarding paint wastewater, little work has been carried out on its electrochemical treatment. K rbahti & Tanyola  (2009) found that a COD removal of about 50% can be achieved after 8 hours of paint wastewater electrolysis at a current density of 66.8 mA/cm² and energy consumption of 79.39 kWh/kg COD.

CONCLUSIONS

This work demonstrates the efficient application of BDD anodic oxidation for the treatment of two different representatives of dye-containing wastewater effluents, namely textile and paint wastewater. A comparison of the performance of the BDD electrochemical cell for the treatment of each wastewater type utilizing chloride and sulfate electrolytes (NaCl and Na₂SO₄) has been made. The comparison was based on different parameters such as COD removal, conductivity, turbidity removal, and color removal. A higher

COD removal efficiency was observed when the anodic oxidation was applied for the treatment of textile wastewater. For both types of effluent the process is favored by using chloride and sulfate ions, which promoted the mediated oxidation supported by the electro-generated chlorine/hypochlorite or peroxydisulfate oxidants. When textile wastewater was treated, a maximum COD removal percentage of 94% was achieved with both chloride and sulfate aqueous solutions. However, for paint wastewater the presence of chloride ions was found to accelerate and enhance the COD removal (85%) compared to the presence of sulfate ions (71%). The COD removal for all tested experiments followed pseudo first-order kinetics. It was also found that adding supporting electrolytes had no significant influence on the ultimate turbidity removal for both textile and paint wastewater, which exceeded 94%. Meanwhile, chloride-containing electrolytes expedited the turbidity removal in textile and paint wastewater although the final turbidity removal percentage was the same for raw and electrolyte-added samples. In the case of textile wastewater treatment, the color removal increased from 84 to 96% when NaCl and Na₂SO₄ were utilized throughout the oxidation process, whereas no significant effect of supporting electrolytes was observed for paint wastewater. The energy consumption per unit COD mass for raw and chloride/sulfate containing samples was evaluated for both textile and paint wastewater. The effect of supporting electrolytes on the specific energy consumption was more noticeable in the case of paint wastewater. The decrease in specific energy consumption in paint wastewater was lower by a factor of 3- and 4-fold when Na₂SO₄ and NaCl were added respectively.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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