Fabrication and application of boron doped diamond BDD electrode in olive mill wastewater treatment in Jordan
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ABSTRACT
A boron doped diamond (BDD) electrode was employed in an electrochemical reactor to oxidize the phenolic content of Jordanian olive mill wastewater. The BDD anode was fabricated using hot filament chemical vapor deposition on niobium and the morphology of the BDD electrode was characterized using an atomic force microscope. Then, electrolysis batch runs were carried out at laboratory scale to test the effect of different process parameters, namely, initial chemical oxygen demand (COD) load (72.9, 33.8, and 0.18 g/L), the addition of Na2SO4 as supporting electrolyte, and adding NaCl along with Na2SO4, on the efficiency of the treatment process. The results were reported in terms of COD, color and turbidity removal, and pH variation. The experiments revealed that electrochemical oxidation using BDD significantly reduced the COD by 85% with no supporting electrolytes. It was observed that adding Na2SO4 with NaCl brought the COD removal to higher than 90% after 7 hours of treatment for COD loads of 72.9 and 33.8 g/L, and after 2 hours for a COD load of 0.18 g/L. Likewise, color was completely removed regardless of the initial COD load. The turbidity for samples with 72.9 and 33.8 g/L as COD load reached a minimal value of 2.5 and 1 NTU respectively.

Key words | advanced oxidation processes, boron-doped diamond electrode, electrochemical oxidation, olive mill wastewater, phenolic compounds

INTRODUCTION
During the last century after the industrial revolution, a large amount of industrial wastewater was discharged into rivers, lakes, soils and coastal areas. Industrial water effluents include water for purposes such as processing, washing, extraction, and cooling in factories that manufacture products (Hanchang 2009). Among these effluents was olive mill wastewater (OMW), which is a liquid by-product generated during olive fruit pressing and processing to extract olive oil. OMW consists of water (80–83%), organic compounds (15–18%), and 2% of inorganic compounds (Chatzisymeon et al. 2009). It is also characterized by very high chemical oxygen demand (COD) (40–200 g/L), biochemical oxygen demand (BOD) (12–60 g/L), total solid contents (40–150 g/L) and a pH of about 5 (Umran et al. 2008). The toxicity of the OMW has been attributed to the high degree of phenolic compounds that are biorecalcitrant and accumulate in water bodies. Hence, large amounts of untreated OMW effluent lead to intense phytotoxic phenomena in flora, and quality degradation of ground water and surface aquatic reservoirs.

Jordan is one of the Middle Eastern countries that suffer from contamination by OMW effluents, particularly in the season of olive oil production. In Jordan, the conventional disposal of OMW can affect the limited water resources, livestock resources, and agricultural resources. To tackle this environmental problem, many researchers have proposed various treatment technologies including chemical,
biological and electrical treatment methods (Lochart 1985; Ju et al. 1991; Boari et al. 1995; Hayek et al. 1996). However, these methods have limitations in their operation. In particular, biological processes need long hydraulic detention times and large reactor volumes (Siringi et al. 2013). In this perspective, advanced oxidation processes for OMW treatment have recently attracted great attention due to their potential to destroy toxic phenolic pollutants. More specifically, the efficiency of electrochemical oxidation of phenol in OMW over non-traditional anodes such as boron-doped diamond (BDD) electrodes has been proposed and reported in the literature by several researchers (Canizares et al. 2006; Chatzisymeon et al. 2009; Elaoud et al. 2011; Bouhssine et al. 2013). Bouhssine et al. 2013 obtained a reduction in the COD of the phenolic compounds of approximately 60 and 63%, respectively, after 30 min of electrooxidation over a BDD anode. Chatzisymeon et al. 2009 tested the treatability of undiluted OMW effluent (40,000 mg/L COD) at 20 A for 15 h, yielding 19% COD and 36% phenols removal respectively. BDD is considered to be an ideal anode for industrial treatment of OMW in Jordan (Ju et al. 1991). Moreover, the BDD thin films have outstanding properties, which are significantly different from those of other traditional electrodes such as glassy carbon or platinum electrodes, and therefore they are attractive for electrolysis applications.

The BDD electrodes have a large potential window in aqueous solution with low background currents (Martin et al. 1996). In addition, the electrodes formed from BDD possess physical properties including hardness, low environmental impact, high hole mobility, and high thermal conductivity (Alfaro et al. 2006). Moreover, the surface of BDD electrodes possesses over-potential to oxygen emission (Bouhssine et al. 2013) and is stable with little evidence of degradation of electrochemical activity with time (Kraft 2007).

Despite the extensive scientific research on OMW treatment by electrochemical techniques, there are no cited papers to our knowledge on the electrolysis of OMW over BDD with high initial COD load and effluent quality that meet the legal discharge requirements.

This work describes the lab preparation of BDD on niobium substrate and its applications in the electrochemical treatment of OMW in Jordan. The performance of the process as a function of the operating parameters such as initial COD load, adding supporting electrolyte, and adding chloride ions along with the supporting electrolyte was evaluated. The OMW electrolysis results were reported in terms of COD, turbidity and color removal.

MATERIALS AND METHODS

Experimental setup

The BDD electrode consists of two expanded identical and parallel pure niobium circular grids (facilitating the gas bubble flow) separated by 2 mm, having a thickness of 2.8 mm and a diameter of 90 mm (total area of 65 cm² per electrode). The electrodes were prepared by hot filament chemical vapor deposition on niobium substrates, which were pretreated by sand blasting to roughen the surface in order to enhance the adhesion strength between the diamond and the substrate as well as to increase the electrochemical performance due to the increase in surface area. The niobium substrates were cleaned twice in ethanol and seeded with diamond powder using an ultrasonic device. The coating process took place in a CVD hot filament coating machine by two parallel filament rows, and the film thickness was measured (8 μm). In order to enhance the doped diamond conductivity, a mixture of CH₄ (1%) and a small amount of B(OC₂H₅)₃ were used in the coating process. All the chemical reactions were carried out under galvanostatic conditions, and the characteristic parameters of the diamond films were performed using an atomic force microscope (AFM).

A laboratory-scale electrochemical reactor (Figure 1) was made of Plexiglas with a 1,000 cm³ capacity to treat OMW. A standard DC power supply was used as the source of electric current for the experiments, and the voltage fluctuations during the reaction were automatically monitored using a digital multimeter. The working electric current was fixed at a constant 3 A. The temperature of the electrolysis reactor was kept constant at room temperature by using an agitated water bath.

Samples were drawn periodically in sealed and clean 20 mL glass vials and analyzed immediately afterwards. The treatment process was tested in terms of COD, color, turbidity removal, and pH variation through the electrolysis time.
OMW samples

Three different raw OMW samples (A, B, and C) were collected in sealable metal containers from the northern part of Jordan (Irbid) during the olive fruit harvesting season of the year 2014 and stored at 4°C. Sample A is the milling wastewater, Sample B is the mixture of olive washing and milling wastewater, and sample C is the washing wastewater. Due to the high content of total suspended solids, the three samples were filtered using a medium crystalline filter paper and then they were centrifuged for 60 minutes at 6,000 rpm. The measurements were repeated to improve averaging. The main physiochemical properties of the three samples prior to and after filtration processes are given in Table 1.

The tested samples were prepared in 1 L volume, and divided into three groups as follows: the first group was the original samples A, B, and C; the second group were A, B, and C samples mixed with Na₂SO₄ as a supporting electrolyte; and the third group were A, B, and C with Na₂SO₄/NaCl electrolyte.

Chemicals and analytical methods

Sodium sulfate Na₂SO₄ (Sigma Aldrich) was used as a supporting electrolyte with a concentration of 0.71% w/v and NaCl (0.06% w/v) (Sigma Aldrich) as a second supporting electrolyte mixed with OMW.

The COD, conductivity, turbidity, pH and absorbance of the samples were investigated and recorded for analysis and comparison.

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

The turbidity of the samples was measured with a Wagtech turbidity meter.

The COD values of the initial and treated samples were determined using the dichromate standard method (APHA 1998). Each sample was introduced into commercially available digestion solution (0–1,500 mg/L) containing potassium dichromate (Hach-Germany); afterward, the solution was incubated at 150°C for 120 minutes in a COD Hach digester (DRB 200-Germany). The COD readings of the electrolyzed samples were measured using a Hach spectrophotometer (DR/2010-Germany).

Table 1 | Physiochemical properties of OMW samples A, B and C before and after filtration processes

| Properties               | A          |          | B          |          | C          |          |
|--------------------------|------------|----------|------------|----------|------------|----------|
|                          | Before     | After    | Before     | After    | Before     | After    |
| pH                       | 4.84       | 5.00     | 4.48       | 4.33     | 6.91       | 7.07     |
| Conductivity (mS)        | 8.75       | 11.37    | 5.82       | 7.41     | 1709       | 1985     |
| Turbidity (NTU)          | 9,354.2    | 283.87   | 2,049.2    | 85.5     | 54.9       | 9.79     |
| Soluble chemical oxygen demand SCOD (g/L) | 72.9 | 33.8 | 2,049.2 | 85.5 | 54.9 | 9.79 |
| Total solids TS (mg/L)   | 59,815     | 59,800   | 27,130     | 24,875   | 2,360      | 2,295    |
| Total volatile solids TVS (mg/L) | 37,020 | 35,350  | 17,295     | 15,600   | 1,220      | 1,090    |

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

The dark color density of OMW samples is an indicator of the polymeric phenolic compounds' concentration, which is responsible for their dark colors. The discoloration during the treatment process could be measured in terms of absorbance, which was measured during electrolysis time at 450 nm with a Wagtech 7100 photometer.

RESULTS AND DISCUSSION

Properties of BDD electrode

The BDD surface was investigated using the AFM technique and characterized by root mean square roughness and average grain size. Figure 2 shows an AFM topography image of the BDD surface. A profile of the AFM image taken along the line in Figure 2(a) is displayed in Figure 2(b). The visible roughness of a few micrometers is a result of surface roughening pretreatment of the niobium substrate. The diamond on the layer surface shows well (111)-faceted crystals with an average grain size of $0.7 \pm 0.3 \mu m$. Importantly, no cracks or holes appear and the peeling phenomenon does not occur, indicating a high quality coating process, which means that the electrode area is totally used for electrochemical oxidation and this consequently increased the electrodes' efficiency.

OMW electrolysis with no added supporting electrolyte

Coloration evolution and absorbance variation during electrolysis

The efficiency of OMW treatment by electrochemical oxidation with a BDD anode was first tested by following up the disappearance of the blackish brown color of the three samples A, B, and C. Results showed that during electrolysis, the dark color of the three samples disappeared gradually and the samples became transparent at the end of the process.

The discoloration of sample A is shown in Figure 3. This observation was confirmed by the absorbance results presented in Figure 4. As illustrated in Figure 4, the absorbance decreased gradually to reach an absorbance reduction of 80, 97, and 98% for samples A, B, and C, respectively. These findings are in accordance with the results of Bouhssine et al. (2013). The initial concentration of organic pollutants is a key factor that affects, to a great degree, the efficiency of OMW electrolysis. Obviously, the maximum absorbance reduction was obtained with the least polluted sample, which is sample C.

Figure 2 | (a) AFM topographies of the BDD layer on niobium substrate. (b) Profile taken along the line in Figure 1(a).
On the other side, the minimum absorbance removal was observed with sample A. This could be attributed to the fact that sample A is heavily polluted, which means implicitly that it contains a higher concentration of phenolic compounds.

COD reduction during electrolysis

In order to verify if the absorbance reduction of the three samples is concomitant with COD removal, the COD reduction was measured against time, as depicted in Figure 5. It is obvious that in all cases the COD removal increased with time to attain a maximum removal of 87, 92, and 89% for samples A, B, and C, respectively. This COD reduction during electrolysis using no supporting electrolyte could be attributed to the generation of hydroxyl radicals (Elaoud et al. 2011) that reacts with polyphenols on the BDD electrode (Martínez-Huitle & Ferro 2006; Panizza et al. 2008).

Turbidity variation during electrolysis

Turbidity was also monitored during the process time. For both samples A and B, the turbidity had a tendency to decrease with time as shown in Figure 6 and it reached values of 10 and 3.6 NTU, respectively. This trend could be justified by the oxidative polymerization of the phenols and tannins originally present in OMW (Assas et al. 2002). However, for sample C, the turbidity fluctuated around an average value of 25 NTU. This instability in turbidity readings could be justified by the formation of small oily micelles in sample C, as it has the lowest oil content (Yang 2007).

pH variation during electrolysis

Figure 7 shows the pH variation during electrolysis. The pH increase observed during OMW electrolysis is a proof of the formation of OH\(^-\). Unbalanced OH\(^-\) and H\(^+\) formation takes place due to the hydrogen evolution reaction and oxygen evolution reaction occurring at the
cathode and anode, respectively (Alencar de Souza & Ruotolo 2013).

OMW electrolysis using Na₂SO₄ and NaCl as supporting electrolytes

Absorbance variation during electrolysis

Figure 8(a)–8(c) depict the effect of Na₂SO₄, when used as supporting electrolyte alone and with NaCl, on absorbance variation during electrolysis. It can be seen that for the three samples A, B, and C the absorbance abatement was enhanced by adding Na₂SO₄ and even more when adding Na₂SO₄ and NaCl simultaneously. It was very likely that the absorbance reduction was boosted by using Na₂SO₄ electrolyte due to the formation of oxidizing species like SO₄²⁻/S₂O₈²⁻ (Saracco et al. 2000). A further decrease in absorbance was achieved by adding both Na₂SO₄ and NaCl, which could be an indication of the generation of chloro-oxidant species such as ClO⁻ (Cheng & Kelsall 2007; Alencar de Souza & Ruotolo 2013). In other words, two secondary oxidants (S₂O₈²⁻ and ClO⁻) are most probably electro-generated on the BDD surface upon the addition of Na₂SO₄ and NaCl, according to the following chemical reactions:

\[
2\text{Cl}^– \rightarrow \text{Cl}_2(g) \leftrightarrow \text{Cl}_2(aq) + 2e^–
\]
\[
\text{Cl}_2(aq) + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{Cl}^– + \text{H}^+
\]
\[
\text{HOCl} \leftrightarrow \text{H}^+ + \text{OCl}^–
\]
\[
\text{HSO}_4^– + \text{OH}^– \rightarrow \text{SO}_4^{2–} + \text{H}_2\text{O}
\]
\[
\text{SO}_4^{2–} + \text{SO}_4^{2–} \rightarrow \text{S}_2\text{O}_8^{2–}
\]

COD reduction during electrolysis

The effect of adding supporting electrolyte on the COD removal % was examined for the three types of OMW A, B, and C. Figure 9(a)–9(c) show the COD removal %
during treatment time for three cases: no added electrolyte, with Na$_2$SO$_4$, and with Na$_2$SO$_4$ and NaCl. It can be noticed that with the three types of OMW, whether electrolyte has been added or not a COD removal % of about 90% was achieved. This percentage is much higher than the removal percentage reported by Giannis et al. (2007) and Chatzisymeon et al. (2009). However, for all samples (A, B, and C) the kinetics of the COD removal was apparently enhanced by the addition of Na$_2$SO$_4$ and better enhancement was achieved by the concomitant addition of Na$_2$SO$_4$ and NaCl. Hence, the most effective electrolyte for COD removal is the Na$_2$SO$_4$/NaCl, which might be a result of the electro-generation of new oxidant species.
along with hydroxyl radicals such as peroxodisulfate and chloro oxidant species (Bouhssine et al. 2013). The final COD values for samples A, B and C supplemented with Na$_2$SO$_4$/NaCl electrolytes were 70, 76, 21 mg/L, respectively. The COD removal % - time plots are in good accordance with the absorbance results found in the previous section, and they follow the same trend.

**Turbidity variation during electrolysis**

The impact of the electrolyte type on the turbidity of the three samples (A, B, and C) is shown in Figure 10(a)–10(c). It is observed that for all samples the turbidity decreased with electrolysis time. However, the lowest values throughout the process time were obtained when adding together Na$_2$SO$_4$ and NaCl as supporting electrolytes. The turbidity of sample A dropped from 10 to 3 NTU, sample B from 2.7 to 0.98 NTU, and sample C from 15 to 8 NTU when using no electrolyte and with Na$_2$SO$_4$/NaCl electrolyte, respectively. This result could be justified by the increase in oxidative polymerization of phenols due to the electro-generation of new oxidant species (Elaoud et al. 2011).

**CONCLUSIONS**

The electrochemical treatment of OMW has been investigated using BDD anodes. This method was an efficient and promising technology for OMW treatment even with no supporting electrolyte. Further enhancement in the electrochemical treatment was gained once a combination of two electrolytes, Na$_2$SO$_4$ and NaCl, was added. This combination of electrolytes was efficient to reach a COD removal higher than 90% after 7 hours of treatment time for samples A and B and 2 hours for sample C. In addition, the dark color of the OMW was completely removed and the three samples turned transparent at the end of the electrolysis. The turbidity of the three samples was also strongly affected by the addition of Na$_2$SO$_4$ and NaCl electrolytes. The turbidity of samples A, B, and C reached minimal values (2.5, 1, and 8 NTU) when both Na$_2$SO$_4$ and NaCl electrolytes were added.

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