Research highlights of the manuscript “Electrochemical treatment of reverse osmosis concentrate on boron-doped electrodes in undivided and divided cell configurations”

- 100% of COD and ~70% of DOC was removed in both cell configurations.

- ~21.7 mg/L of AOCl and ~2.3 mg/L of AOBr was formed regardless of the membrane use.

- The TEQ was far lower than expected given the high AOCl concentrations.

- The undivided cell consumed lower energy compared to the divided cell.
Electrochemical treatment of reverse osmosis concentrate on boron-doped electrodes in undivided and divided cell configurations

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Abstract

An undivided electrolytic cell may offer lower electrochlorination through reduction of chlorine/hypochlorite at the cathode. This study investigated the performance of electrooxidation of reverse osmosis concentrate using boron-doped diamond electrodes in membrane-divided and undivided cells. In both cell configurations, similar extents of chemical oxygen demand and dissolved organic carbon removal were obtained. Continuous formation of chlorinated organic compounds was observed regardless of the membrane presence. However, halogenation of the organic matter did not result in a corresponding increase in toxicity (Vibrio fischeri bioassay performed on extracted samples), with toxicity decreasing slightly until 10 Ah L⁻¹, and generally remaining near the initial baseline-toxicity equivalent concentration (TEQ) of the raw concentrate (i.e., ~2 mg L⁻¹). The exception was a high range toxicity measure in the undivided cell (i.e., TEQ=11 mg L⁻¹ at 2.4 Ah L⁻¹), which rapidly decreased to 4 mg L⁻¹. The discrepancy between the halogenated organic matter and toxicity patterns may be a consequence of volatile and/or polar halogenated by-products formed in oxidation by OH⁺ electrogenerated at the anode.

The undivided cell exhibited lower energy compared to the divided cell, 0.25 kWh gCOD⁻¹ and 0.34 kWh gCOD⁻¹, respectively, yet it did not demonstrate any improvement regarding by-products formation.

Keywords: Electrochemical oxidation, Reverse osmosis brine, Boron-doped diamond, Electrolytic cell configuration, Vibrio fischeri bioassay
1. Introduction

For the degradation of organic pollutants, electrochemical oxidation offers an alternative to the existing advanced oxidation processes by eliminating the need to use chemicals to generate highly reactive OH\(^-\). In electrochemical oxidation, OH\(^-\) is generated by water electrolysis at the anode surface. Recently developed boron-doped diamond (BDD) electrodes have received great attention due to a much wider potential range for O\(_2\) evolution in aqueous electrolytes, which allows efficient formation of OH\(^-\) and other reactive oxygen species [3,4]. BDD electrodes have been investigated for electrochemical oxidation of saline wastewater such as landfill leachate and reverse osmosis concentrate [5-8]. Due to the high content of recalcitrant organic compounds, these streams require an on-site treatment before being discharged into the receiving water bodies [9]. High concentrations of dissolved salts (i.e., chloride ions > 1 g L\(^{-1}\)) contained in landfill leachate and reverse osmosis concentrate are attractive for electrochemical processes as they provide a lower internal ohmic resistance, thus reducing the energy demand of the process. However, electrochemical oxidation is expected to generate active chlorine species (e.g., Cl\(_2\), HClO/ClO\(^-\)) that may increase the toxicity of the treated stream due to the presence of chlorinated by-products [6,10]. The extent of chlorinated organic compounds formed in electrochemical oxidation depends on the initial characteristics of the stream (e.g., concentrations of chloride ions and organic pollutants) and reactor design and operation (e.g., applied current/potential and cell configuration) [11,7].

A number of studies on electrochemical treatment of municipal wastewater reverse osmosis concentrates have been conducted [6-9, 12-14]. These have mainly been focused on the evaluation of the performance of BDD and other anode materials,
and effect of current density and chloride ions concentration on the electrochemical oxidation in the undivided (membraneless) electrolytic cell [6-8, 12]. Also, a three-dimensional electrode reactor using γ-Al₂O₃/Sn-Sb oxide as particle electrodes has been recently developed for the electrochemical treatment of reverse osmosis concentrates [13]. Hurwitz et al. [14] reported an efficient oxidative degradation of organic matter using a hybrid ultraviolet (UV) and electrochemical oxidation process, which also yielded lower amounts of trihalomethanes compared to the stand-alone electrochemical oxidation.

This study investigates the effect of reactor design on the performance of electrochemical oxidation of reverse osmosis concentrate by comparing undivided and membrane-divided electrolytic cell. The undivided cell configuration offers operation at circumneutral pH without the need for pH correction of the treated effluent, and possibly lower energy consumption for reaching specific treatment objectives due to a lower internal resistance. Additionally, in-situ cathodic reduction of active chlorine, i.e., HClO/ClO⁻ species, may lower their bulk concentration and thus decrease the extent of electrochlorination of the organic matter in the undivided cell. Although BDD electrodes have been mainly investigated as anodes, several studies reported excellent performance of cathodically polarised BDD [15,16]. For example, BDD was capable of reducing efficiently bromate to bromide ions [15], and reductively dechlorinating trichloroethylene to acetate and chloride ions, without any intermediate products [16]. Thus, some of the formed organohalogen by-products may also be reduced at the BDD cathode. To the best of our knowledge, comparison of electrochemical oxidation of reverse osmosis concentrate in divided and undivided cell configurations has not been reported in literature. Moreover, the formation of adsorbable organic halogen (AOX) and toxicity response to Vibrio fischeri of the
oxidised concentrate are also reported, emphasising the need for an integrated approach of combined bioassays and chemical analysis in the assessment of treatment performance.

The treatment efficiency was assessed in terms of chemical oxygen demand (COD) and dissolved organic carbon (DOC) removal. Residual free chlorine and total chlorine were also determined. The formation of halogenated by-products was evaluated based on the measurement of the halogen-specific AOX, i.e., adsorbable organic chlorine (AOCl), bromine (AOBr), and iodine (AOI). Finally, the changes in non-specific, baseline toxicity of the treated stream were evaluated in bioluminescence inhibition test (Microtox) using \textit{Vibrio fischeri}.

2. Experimental

2.1. Reverse osmosis concentrate

The reverse osmosis concentrate was collected in a single sampling batch from the concentrate stream of a reverse osmosis unit process at an inland water recycling plant reclaiming a mixture of secondary-treated effluents. Measured characteristics of the concentrate are detailed in Table 1.

2.2. Experimental set-up

The undivided electrochemical cell was comprised of one rectangular Perspex frame (internal dimensions of \(20 \times 5 \times 2\) cm, equal to net active volume \(V_{ACT}\) of 190 mL), bolted in between two Perspex plates. The divided electrochemical cell was identical to the undivided one, but constructed using two rectangular frames of identical size, with a cation exchange membrane (CMI-7000, Membranes International, U.S.A.) placed between anode and cathode. Two monopolar Si/BDD plate electrodes
purchased from Adamant Tech., Switzerland (each 4.8 × 8.5 × 0.2 cm; active area of 40.8 cm²; 2-3 µm coating thickness of 500 ppm boron) were used as anode and cathode in the undivided cell, with an inter-electrode gap of 1 cm. In the divided cell, the Si/BDD electrode was used as the anode and a stainless steel plate of the same size and shape was used as the cathode. In this case, the reverse osmosis concentrate was treated only in the anodic compartment of the cell. The cathode side in the divided cell was applied only as electron sink, and was expected not to affect the oxidation processes [17]. An Ag/AgCl reference electrode (3 M KCl, 0.210 V vs. standard hydrogen electrode (SHE), Bio-analytical, U.S.A) was used in both cell configurations.

In both undivided and divided cell, batch mode electrochemical oxidation experiments were conducted at constant current of 510 mA (anode potential, $E_{AN} = +3.9$ V vs. SHE) using a galvanostat (KP07, Bank Elektronik, Germany). Data was recorded every 60 s using an Agilent 34970A (U.S.A.) data acquisition unit. A total volume ($V_{TOT}$) of 5 L of reverse osmosis concentrate was continuously recirculated through each cell during 120 h at a rate of 120 mL min$^{-1}$. $V_{ACT}$ is the net active volume of reverse osmosis concentrate electrochemically treated inside the reactor, while $V_{TOT}$ is the total volume of the concentrate recirculated during the batch electrochemical treatment. The ratio of $V_{ACT}/V_{TOT}$ in both cell configurations was the same, i.e., 0.038. In the case of the divided cell, 5 L of 0.5 M H$_2$SO$_4$ solution was recirculated as catholyte to avoid the formation of a precipitate at the stainless steel cathode, as a result of diffusion of Ca$^{2+}$ ions from the concentrate through the cation exchange membrane and pH increase in the cathodic compartment. The pH in the undivided cell was in the range of 6-7 without pH adjustment, whereas in the divided cell, the pH was maintained at pH 6-7 by an automatic dosing of small aliquots of 3 M
NaOH solution. The pH and temperature values were monitored overtime using an Endress+Hauser pH controller (Germany).

2.3. Analytical methods

Samples (110 mL) collected after 0, 24, 48, 72, 96, and 120 h of electrooxidation were filtered using a 0.22 µm Millipore syringe unit. COD, residual free chlorine and total chlorine concentrations were measured directly after sampling. COD was determined using the COD tests range 10-150 mg L\(^{-1}\) (Merck) by a spectrophotometric method. The DOC concentration was analysed using an Analytik Jena multi N/C®-series instrument. Residual free chlorine and total chlorine were measured with the \(N,\text{N-}\)diethyl-p-phenylenediamine (DPD) ferrous titrimetric method. It should be noted that residual oxidants other than chlorine present in the solution (e.g., \(\text{H}_2\text{O}_2\), \(\text{O}_3\)) may react with DPD similarly to chlorine, thus possibly interfering with the chlorine measurements. The remaining samples were then quenched by adding specific aliquots of 0.71 M \(\text{Na}_2\text{SO}_3\) solution, i.e., 1.2 mol of sulphite per mol of HClO (assuming all residual chlorine was in HClO form), in order to eliminate further reaction of chlorine. The quenched samples were then subjected to analysis of DOC and AOX concentrations, and to a solid phase extraction (SPE) procedure for Microtox analyses [18]. Sample extraction was conducted directly after quenching of \(\text{Na}_2\text{SO}_3\) to the samples.

The Microtox (\(V. \text{fischeri}\)) bioassays were performed on the samples extracted by a solid phase extraction (SPE) procedure, as described previously [19]. The bioassay could not be performed on the non-extracted samples since chlorine, chloramine and other oxidants contained in the electrooxidised concentrate are toxic to the bacteria. Halogen-specific AOX was analysed using the analytical method
described in Kristiana et al. [20]. Details on the Microtox and AOX analyses are given in Text A1 (Supporting Information). The halide ions (Cl⁻, Br⁻, and I⁻) were analysed using ion chromatography (Dionex ICS 3000). In all experiments, duplicate analyses were performed, and the obtained data was reported as a mean values with their standard deviations.

3. Results and Discussion

3.1. Formation of active chlorine, and removal of COD and DOC

The concentrations of chloride and bromide ions in the raw reverse osmosis concentrate were 1.39±0.07 g L⁻¹ and 3.06±0.03 mg L⁻¹, respectively, while iodide ions were below the detection limit (i.e., <0.001 mg L⁻¹, see Table 1). As shown in Figure 1, the kinetics of oxidation of chloride ions were identical in the undivided and divided cell, and 92% of Cl⁻ was consumed at the applied charge, \( Q = 13.4 \text{ Ah L}^{-1} \). At anodes with high overpotential for O₂ evolution such as BDD, the oxidation of chloride ions is kinetically favoured [21]. Also, in the divided cell where cathodic reduction of chlorine species was not possible, up to 473 mg L⁻¹ of residual free chlorine was accumulated at 7.7 Ah L⁻¹ (Figure 1). A similar maximum concentration of 450 mg L⁻¹ of free chlorine was measured in the undivided cell at \( Q = 5.0 \text{ Ah L}^{-1} \), suggesting that the reduction of HClO/ClO⁻ species at the BDD cathode was insignificant. Previously, efficient electrochemical reduction bromate [15], nitrate [22] and Cr(VI) ion [23] was observed at cathodically polarised BDD electrodes. Here, it could be hypothesised that the cathodic reduction of HClO/ClO⁻ species to chloride ions was followed by their fast re-oxidation at the anode, thus maintaining the bulk concentration of active chlorine at a similar levels in the undivided and membrane-divided cells.
Figure 2 depicts COD and DOC removals in the two investigated reactor configurations. Complete removal of COD was achieved after 5 Ah L⁻¹, and ~70% DOC removal was obtained after 13.4 Ah L⁻¹ in both cell configurations. Previous studies of electrochemical oxidation of reverse osmosis concentrate using an undivided cell reported complete COD removal at lower applied charge, i.e., at 1-2.5 Ah L⁻¹ [7,8]. Here, a higher charge required to achieve complete COD removal was due to a lower ratio of \( V_{\text{ACT}}/V_{\text{TOT}} \).

Similar extent of oxidative degradation of organics in the two cell configurations suggests a similar contribution of the electrogenerated OH⁻ and other reactive species including chlorine species, to the overall oxidation. In addition, faster COD removal than DOC removal implies the formation of persistent oxidation by-products, e.g., chlorinated organic compounds [6,24].

In the case of undivided cell, a local increase in pH at the cathode surface led to scaling and formation of insoluble precipitates of Ca²⁺ and Mg²⁺ ions that diffused from the reverse osmosis concentrate through cation exchange membrane to the cathode compartment. However, the precipitate was formed only at the non-coated side of the monopolar BDD cathode, i.e., the silicon surface. Since the BDD-coated side of the electrode did not exhibit any scaling, the formed precipitate did not lead to an increase in the total cell potential \( (E_C) \), which remained constant at 6.9 V. However, cathode scaling would lead to maintenance issues in long-term operation, e.g., due to reactor tubing blockage. Higher internal resistance in the divided cell increased the total cell potential to 9.5 V. Therefore, estimation of energy consumptions invested to achieve complete COD removal after 5 Ah L⁻¹ in the divided cell was 0.34 kWh g COD⁻¹, higher than in the case of undivided cell, i.e., 0.25 kWh g COD⁻¹. Previously, Van Hege et al. [8] and Zhou et al. [12] reported 0.20
kWh g COD$^{-1}$ of energy consumption for complete COD removal in electrooxidation of reverse osmosis concentrate on BDD electrodes using undivided cells. At the end of electrooxidation ($Q=13.4$ Ah L$^{-1}$) when 70% DOC removal was achieved, the amount of energy consumed in the divided and undivided cell were 127 kWh m$^{-3}$ (i.e., 4.7 kWh g DOC$^{-1}$) and 92 kWh m$^{-3}$ (i.e., 3.4 kWh g DOC$^{-1}$), respectively.

3.2. Formation of halogenated by-products

Figure 3 shows the formation of AOCl and AOBr vs. applied charge during the electrooxidation experiments. AOI was only detected in the untreated brine sample at a concentration of 0.230 ± 0.003 mg L$^{-1}$, and was rapidly degraded at the beginning of the experiments. The AOBr reached its peak concentration at 2.4 Ah L$^{-1}$ (1.51 ± 0.01 mg L$^{-1}$) and 5.0 Ah L$^{-1}$ (2.30 ± 0.01 mg L$^{-1}$) in the undivided and divided cells, respectively, and was further decreased due to oxidative degradation of brominated organic compounds. However, more than 92% of AOX was in the form of AOCl due to the high concentration of chloride ions in the reverse osmosis concentrate. Formation of persistent AOX has been previously observed in electrochemical oxidation of reactive dyes and pharmaceuticals at BDD and mixed metal oxide electrodes [10,25]. The concentration of chlorinated organic by-products increased with the applied charge in both divided and undivided cell, reaching 20.7 ± 0.4 and 21.7 ± 0.1 mg L$^{-1}$, respectively, at 13.4 Ah L$^{-1}$. Thus, undivided cell offers no advantage in terms of AOCl formation compared to the divided cell. Moreover, considering the molar ratios of the remaining DOC and AOCl of 1.0:0.6 and 0.85:0.6 in the divided and undivided cell, respectively, the undegraded organic fraction contained a large amount of polychlorinated organic compounds that would likely
require longer electrochemical oxidation time and/or higher applied potentials to be further oxidised. This would be uneconomic regardless the cell configuration used.

3.3. Evolution of toxicity towards Vibrio fischeri

The bioluminescence inhibition test (Microtox) using Vibrio fischeri is a non-specific toxicity test that determines the overall mixture toxicity effect of a wide variety of organic contaminants and other chemicals present in samples [19]. As it was not possible to simultaneously quench different oxidant species (e.g., HClO, ClO₂, H₂O₂, OH⁻, HO₂⁻, O₃) present in the treated sample without interfering with the Microtox test [19], all bioassays were performed on the SPE treated samples. Figure 4 illustrates the evolution of baseline-toxicity equivalent concentrations (TEQ) in the two investigated cell configurations. Compared to the toxicity of the untreated concentrate, somewhat lower toxicity was observed in the divided cell in the first 10.5 Ah L⁻¹. In the case of the undivided cell, a sharp increase in baseline-TEQ was observed at 2.4 Ah L⁻¹ (i.e., up to 10.71±0.39 mg L⁻¹), suggesting the initial abundant formation of more toxic oxidation by-products. Baseline-TEQ values determined for the subsequent samples from the undivided cell seemed to be similar to the ones measured in the divided cell at the same applied electrical charge. In the final sample at 13.4 Ah L⁻¹, the baseline-TEQ in the divided cell was 2.02 ± 0.51 mg L⁻¹, similar to the toxicity of the untreated concentrate (i.e., 2.29 ± 0.15 mg L⁻¹), while in the undivided cell it was slightly increased to 3.97 ± 0.18 mg L⁻¹. Decrease in toxicity at the applied charge between 2.4-7.7 Ah L⁻¹ may be associated with the decrease in AOBr concentration, as at 7.7 Ah L⁻¹ the concentration of AOBr observed in both cells was lower than 1 mg L⁻¹. Previously, Neale et al. [26] observed a simultaneous increase in the non-specific toxicity and AOBr formation during disinfection of
drinking water. Also, several studies have characterised brominated organic compounds to be more toxic than their chlorinated counterparts [27,28]. At the end of the electrochemical oxidation \((Q = 13.4 \text{ Ah L}^{-1})\), AOCl concentrations increased to 20.7-21.7 mg L\(^{-1}\), which may have contributed to a slight increase in baseline-TEQ concentrations. Since the SPE cartridge used in the current study is capable of retaining a wide range of compounds, particularly the more hydrophobic species, and chlorination typically increases the hydrophobicity of a molecule, it was expected that the same sort of compounds would be adsorbed to the activated carbon in the AOX analysis. Nevertheless, the overall trend in baseline-TEQ did not correlate with the organochlorine and organobromine by-products formed during electrooxidation of reverse osmosis concentrate. Chlorinated and particularly brominated organics (e.g., (halo)acetic acids, phenols) have often been reported to be more toxic than their non-halogenated equivalents [27,29]. Yet, there is no scientific consensus on the correlation between the toxicity and AOX measurements [30,31]. We hypothesise that the discrepancy between AOX and toxicity profiles is not an indication of the lower toxicity of halogenated by-products, but rather a consequence of their poor retention on the SPE cartridges in the sample preparation step. Also, AOX should be considered as a surrogate measurement for the halogenated organic by-products, rather than their absolute measure, since it is difficult to achieve their complete recovery from real wastewater samples [32].

It is noteworthy that the overall baseline-TEQ values measured in this study are significantly lower than the baseline-TEQ values observed in our previous study on mixed metal oxide electrodes using the same SPE protocol and \(V. fischeri\) bioassay [33]. For example, the baseline-TEQ of reverse osmosis concentrate oxidised at BDD electrodes in the divided cell did not exceed 4 mg L\(^{-1}\) measured at 13.4 Ah L\(^{-1}\). The
baseline-TEQ of concentrate oxidised at Ti/Pt-IrO₂ electrodes using the same experimental set-up was increased up to 165 mg L⁻¹ already at 0.55 Ah L⁻¹ [33]. Although a different batch of sample was used in each study, both concentrates were originating from the same wastewater recycling plant, and the difference in concentrations of general parameters (e.g., COD, DOC and Cl) was not substantial. Therefore, while oxidation of concentrate at Ti/Pt-IrO₂ anode led to a 50-fold increase in toxicity, the same bioassay showed less than 5-fold increase in toxicity in the case of BDD anode. This result suggests the formation of different halogenated organic by-products during electrooxidation of the reverse osmosis concentrate at the BDD electrode, compounds which are possibly not retained well by the solid phase during SPE, or are volatile and lost during SPE pre-treatment. Due to a greater capability of BDD electrodes to generate OH⁻ [3], the bond breaking and hydroxylation oxidation reactions that occur concomitantly with electrochlorination may lead to the formation of more polar and/or lower molecular weight fractions of AOX, which may not be well-retained or lost during SPE extraction and thus would not be fully measured in the baseline toxicity analysis. Characterisation of AOX formed in electrochemically-oxidised effluents requires further investigation, and the toxicity of the formed AOX needs to be determined by additional bioassays and extraction studies.

4. Conclusions

Both undivided and membrane-divided cells performed in a similar way in terms of free chlorine generation, and removal of COD and DOC (i.e., complete removal of COD and ~70% DOC removal). The formation of chlorinated and brominated organic by-products was determined to be similar for the two configurations. The AOCl concentration was continuously increased from 0.73-0.78 mg L⁻¹ to 20.7-21.7 mg L⁻¹
at 13.4 Ah L$^{-1}$. AOBr reached its peak concentrations of 1.51-2.30 mg L$^{-1}$ at 2.4-5 Ah L$^{-1}$, and was further decreased due to oxidative degradation of brominated organics. However, the toxicity to *V. fischeri* was far lower than expected given the high AOCl concentrations. It can be anticipated that more volatile halogenated and lower molecular weight by-products are formed in electrooxidation at BDD anode, which would be lost in the sample pre-treatment step. Given that the composition of the AOX formed in electrochemical treatment is largely unknown, development of a bioanalytical tool capable of providing a more sensitive response to mixture toxicity is necessary in order to estimate the true risk of environmental application of electrochemical processes.

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**References**


Supporting Information


Figure captions

Figure 1. Removal of chloride and evolution of residual free chlorine and total chlorine during electrochemical oxidation of reverse osmosis concentrate in undivided (closed symbols) and divided (open symbols) electrochemical cells. Note: ⚪, free chlorine; ▲, total chlorine; ◆, chloride ions. The error bars correspond to the standard deviation of duplicate analyses.

Figure 2. Removal of COD and DOC (normalised to the initial values) during electrochemical oxidation of reverse osmosis concentrate in undivided (closed symbols) and divided (open symbols) electrochemical cells. Note: ▲, COD/COD₀; □, DOC/DOC₀. Error values were lower than 5%.

Figure 3. Formation of halogen-specific AOX during electrochemical oxidation of reverse osmosis concentrate in undivided (closed symbols) and divided (open symbols) electrochemical cells. Note: ■ and □ represent AOCl, while ⚪ and ◆ represent AOBr. AOCl and AOBr is expressed as mg Cl⁻ L⁻¹ and mg Br⁻ L⁻¹, respectively. AOI
was only detected in the initial sample, at 0.230 ± 0.003 mg L⁻¹ (as I⁻), in both cells. The error bars correspond to the standard deviation of duplicate analyses.

Figure 4. Baseline-TEQ concentrations during electrochemical oxidation of reverse osmosis concentrate on BDD electrodes in undivided and divided cells. Note: Dashed arrows show decrease and increase in baseline-TEQ of oxidised reverse osmosis concentrate in both cell configurations. The error bars correspond to the standard deviation of duplicate analyses.
Table 1. Physico-chemical characteristics of the untreated reverse osmosis concentrate used in the current study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value*</th>
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<tr>
<td>pH</td>
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<tr>
<td>Conductivity</td>
<td>mS cm⁻¹</td>
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<tr>
<td>COD</td>
<td>mg O₂ L⁻¹</td>
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<tr>
<td>DOC</td>
<td>mg C L⁻¹</td>
<td>39 ± 3</td>
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<tr>
<td>Cl⁻</td>
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<td>Br⁻</td>
<td>mg L⁻¹</td>
<td>3.06 ± 0.03</td>
</tr>
<tr>
<td>I⁻</td>
<td>mg L⁻¹</td>
<td>Below detection limit (&lt; 0.001)</td>
</tr>
</tbody>
</table>

* The error values correspond to the average deviation of duplicate analyses.
Figure 2

The graph illustrates the relationship between COD/COD$_0$ and DOC/DOC$_0$ versus $Q$ (Ah L$^{-1}$). The data points are represented by different symbols for each condition, with lines connecting them. The graph shows a decrease in COD/COD$_0$ and DOC/DOC$_0$ as $Q$ increases.
Figure 3

The graph shows the relationship between Q (Ah L⁻¹) and [AOCl], mg L⁻¹ (open circles) and [AOBr], mg L⁻¹ (squares). The figure illustrates the variations in [AOCl] and [AOBr] as Q increases. The peaks and troughs indicate the changes in concentration levels at different Q values.
Figure 4

The graph shows the relationship between Baseline-TEQ (mg L\(^{-1}\)) and Q (Ah L\(^{-1}\)). The data points are differentiated by the type of cell: undivided (closed triangle) and divided (open circle). The x-axis represents Q (Ah L\(^{-1}\)) ranging from 0 to 16, and the y-axis represents Baseline-TEQ ranging from 0 to 12 mg L\(^{-1}\).