# Algal Removal from Water by Electrochemical Generation of Hydrogen Peroxide and Persulfate

**Intesar K. Abdulhassan[1], Adel F. Hamed[2], Hesham M. Abd El Fatah[2], Gamal O. El-Sayed[3,*]**

[1]Sciences Department, College of Basic Education, University of Diyala, Iraq
[2]Botany Department, Faculty of Science, Ain Shams University, Cairo, 11566, Egypt
[3]Chemistry Department, Faculty of Science, Benha University, Benha, Egypt
*Corresponding Author: gamaloelsayed@yahoo.com

## ABSTRACT
Removal of algae by electrochemical treatments through electrochemical generation of persulfate and hydrogen peroxide was investigated in a fixed bed reactor. The cell was equipped with two electrodes (two identical graphite anode and cathode). The effect of different operative parameters, such as applied potential and amount of initial sodium sulfate added in the case of persulfate production was evaluated. In addition, the influences of potential differences in the case of hydrogen peroxide production were addressed. The two treatments were optimized, and their high efficacy in removing algae-laden water was proved upon application to collected samples obtained from the reservoir of Rod El-Farag drinking water station. The pro-type system used with the proposed methods is simple, fast, and effective to remove algae from water sources.

## INTRODUCTION

Drinking water quality varies greatly from place to another, depending on the source of water and the conditions. Thus, it's important to ensure the safety of drinking water through various certified methods of analysis in order to choose the appropriate methods of treatment. Sources of municipal water may be contaminated by natural pollutants including chemical and biological. These methods are limited by several factors such as efficiency, formation of secondary pollutants, costs and treatment time (**Robertson *et al*., 2012**). Therefore, recent studies have focused on the instant need for new technical applicable methods to solve the problem of overgrowing and propagation of algae inhabiting the surface waters.

Algae in water are of great concern since they adversely affect drinking water quality and water treatment processes. In particular, in tropical and semi-tropical zones, algae can grow excessively under high nutrient contents in surface water due to contamination by agricultural activity, domestic wastewater discharge and industrial effluents. The high concentrations of nitrogen and phosphorous can provide the ideal medium for the excessive growth of algae, which is detrimental not only from an environmental point of view but also for human health (**Sathe *et al*., 2016**).

_____

Algae may cause problems such as poor taste and odor in the water, and several studies in the literature have addressed the possible problems connected with toxins released by algae. The presence of sub-lethal doses of cyanotoxins in drinking water is implicated as one of the key risk factors for the high occurrence of primary liver cancer.

Conventional treatment methods of fresh water include physical, chemical and biological techniques as coagulation, air flotation, flocculation, sedimentation, chemical oxidation, electrochemical techniques, photolysis using ultraviolet (UV) radiation and chlorine disinfection, which can remove most of the algal cells (**Mascia *et al.*, 2013; Wang *et al.*, 2018**). It is important to remove the algal cells by filtration prior to the addition of any oxidant such as chlorine.

Oxidation disinfection of biological contaminants by chemical agents has been studied using halogens, ozone, hydrogen peroxide, hypohalous salts and silver cations. Physical processes comprise thermal treatment, ultrasonic and electromagnetic radiation as ultraviolet (UV) light and X-ray in addition to filtration with suitable filters (**Yu *et al.*, 2022**). Recent researches have been published about algal removal or deactivation by several techniques including electrocoagulation (**Azarian *et al.*, 2007**), electrochemical oxidation (**Mascia *et al.*, 2013**), coagulation (**Dai *et al.*, 2020; Ren *et al.*, 2022**) and photocatalysis (**He *et al.*, 2021; Mohan *et al.*, 2022**).

Electrochemical disinfection of water is a new technique which has gained increasing interest because of the growing need to disinfect the drinking water, wastewater and pool water (**Bergmann, 2021**). Electrochemical disinfection is mainly based on the oxidation power of disinfectants produced on the electrode surface or the bulk of an electrolyte (**Bruguera-Casamada *et al.*, 2016; Ghernaout, 2017**). In case of chlorine-based electrochemical drinking water disinfection, new activities in the field were observed to replace pressurized chlorine gas with chlorine containing solutions produced electrochemically (**Martínez-Huitle & Brillas, 2008**), often working at low chloride concentration. Chlorine dioxide ($ClO_2$) can be electrochemically produced onsite using undivided electrochemical or divided cells by anodic chlorite oxidation or cathodic chlorate reduction (**Sivey *et al.*, 2010**). The production of ozone on $PbO_2$, platinum, $SnO_2$ and other anodes has been studied (**Park *et al.*, 2019**). Another work on the production of $O_3$ gas on BDD anodes in divided cells was found to be more efficient (**Lara-Ramos *et al.*, 2020**).

The synthesis of $H_2O_2$ by the electrochemical reduction of $O_2$ is also a promising technique. Hydrogen peroxide is one of the most environmentally friendly as it decomposes into oxygen and water and does not release any harmful compounds after reaction (**Drougi *et al.*, 2001**). In this process, a noble metal, metal alloy or carbon-based material is used as a catalytic material either individually or in combination (**Chen *et al.*, 2018**). The use of carbon-based materials has been accelerated because of their high performance, appropriate strength and economic benefit. Many research attempts for improving yield of $H_2O_2$ are focused on higher productive and cheaper electrocatalysts (**Jung *et al.*, 2020; Zhang *et al.*, 2020**). Among the catalysts recently considered, noble metals, alloys and metal oxides could be used. When this process occurs on graphite cathodes, it is performed through the reduction of molecular oxygen (**Perry *et al.*, 2020**).

The reduction of oxygen is described by the following equations depending on the applied potential:

● 4-electron reaction:

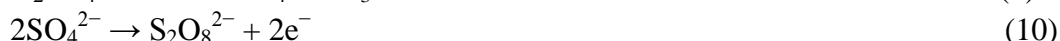$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \text{ (+1.23 V vs. NHE)} \tag{1}$$

● 2-electron reaction:

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \text{ (+0.68 V vs. NHE)} \tag{2}$$

The overall process involves the formation of various radical species such as superoxide $O_2^{\bullet-}$ and hydroperoxide $HOO^{\bullet}$ (**Collin, 2019**). Hence, controlled electrochemical oxidation of water may control the production of hydroperoxyl radical, hydrogen peroxide and hydroxyl radical (**Anantharaj et al., 2021**). Depending on the applied potential, the reaction products may vary according to the equations (3-6):

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-, E = 1{:}229 \text{ V vs. RHE} \tag{3}$$

$$2H_2O \rightarrow HO_2^{\bullet} + 3H^+ + 3e^-, E = 1{:}655 \text{ V vs. RHE} \tag{4}$$

$$2H_2O \rightarrow H_2O_2 + 2H^+ + 2e^-, E = 1{:}760 \text{ V vs. RHE} \tag{5}$$

$$H_2O \rightarrow HO^{\bullet} + H^+ + e^-, E = 2{:}730 \text{ V vs. RHE} \tag{6}$$

The order of oxidizing capability of the reactive oxygen species are arranged as hydroxyl radical > hydrogen peroxide > hydroperoxyl radical > dioxygen (**Wang et al., 2021**).

The theoretical required potential for the chemical reaction shown in Eq. (5) is 1:23 V. Actually, about 1.5–1:7 V is required for the reaction because of various voltage losses. About 1.7–2:0 V is required in the onsite hydrogen peroxide production system, which is considered due to oxygen overpotential (**Song, 2020; Alayande & Hong, 2022**).

The electrochemical production of persulfate is performed in sulfate-containing solutions from the oxidation of $SO_4^{2-}$ and $HSO_4^-$ ions through the reactions described by the equations (7) and (8), respectively (**Fernandes et al., 2021**).

$$SO_4^{2-} \rightarrow SO_4^{\bullet-} + e^- \tag{7}$$

$$HSO_4^- + {}^{\bullet}OH \rightarrow SO_4^{\bullet-} + H_2O \tag{8}$$

$$H_2SO_4 + {}^{\bullet}OH \rightarrow SO_4^{\bullet-} + H_3O^+ \tag{9}$$

$$2SO_4^{2-} \rightarrow S_2O_8^{2-} + 2e^- \tag{10}$$

Electrochemically produced sulfate radical (Equations (7) and (8)), which presents higher oxidizing potential (E 2.6 V/SHE) than that of a hydroxyl radical (E 2.01 V/SHE), promotes a non-selective oxidation resulting in an efficient removal of a wide range of organic compounds (**Shafiee et al., 2018**). Furthermore, the half-life time of $SO_4^{\bullet-}$ is usually longer than that of ${}^{\bullet}OH$, enabling better mass transfer and contact with the organic substrate in solution.

The aim of the present work was to examine the ability of electrochemically generated persulfate and hydrogen peroxide to remove different types of algae. The target of this study was the drinking water source supplying fresh water to Rod El-Farag drinking water station in Great Cairo area. The experiments were performed at the laboratory scale.

_____

## MATERIALS AND METHODS

**Chemicals**

All reagents and chemicals used in the experiment were of analytical grade purity and were used without further purification. Chemicals used in this study were: sodium sulfate ($Na_2SO_4$), sodium persulfate ($Na_2S_2O_8$), sodium thiosulfate $Na_2S_2O_3.5H_2O$ and iodine ($I_2$),

**Apparatus**

A 100mL glass cylinder cell was used as the electrolysis cell with two graphite electrodes ($2\times0.8\times0.4$ cm). Both the anode and cathode had a working surface area of about 6cm$^2$. 100mL of working solution (50mL of raw water diluted with 50mL of distilled water) was taken for the experimental work. The working electrodes were connected together through external wires, while the potential was adjusted to the desired value. All experiments were conducted at room temperature (25°C $\pm$ 2°C). The apparatus used in this research is shown in Fig. (1).
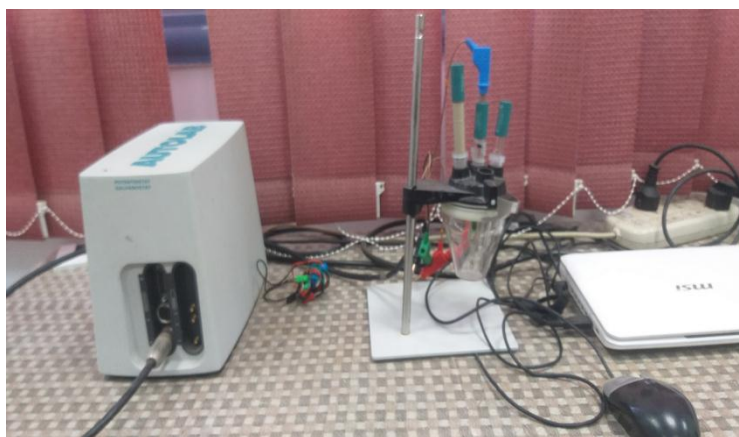


**Fig. 1.** Electrolysis apparatus with the working cell

**Sampling of algae**

Algal samples were seasonally collected during the years 2021-2022 from the drinking water station (Rod El-Farag station, Cairo Governorate, Egypt) by using phytoplankton net of 15 micrometer mesh. In a cleaned plastic bottle, each sample collected was concentrated several times to reach a volume of 100ml. The samples were subjected and transferred to the laboratory in an ice box for the identification and counting of the total algal biomass **(Round _et al_., 1990; Li _et al_., 2021)**.

**Physicochemical characters of water samples**

The essential parameters of raw water taken from the station were measured in two seasons (spring and winter) to determine the water quality of the analyzed samples according to the methods provided by **APHA (2005)**. Some parameters (pH, turbidity, dissolved oxygen) were measured in the field, while other parameters were stored in clean plastic bottles in the refrigerator and analyzed at the Lab a few hours after arriving from the field.

**Electrolysis method**

1- In case of persulfate, 50ml of the required concentration of $Na_2SO_4$ solution was placed with 50ml of pure water or raw water sample and placed in the electrolysis cell. The final concentration of sodium sulfate was 2.5, 5.0, 7.5 and 10% (by weight), then the electrode was lowered into the cylinder, and the electrical voltage was adjusted at 2.0 or 2.5 volts. The time of electrolysis was adjusted at a fixed period of an hour. An excess of solid KI was added to react with the liberated persulfate, giving ab equal amount of $I_2$. The liberated iodine was titrated with a standard solution of sodium persulfate to calculate the amount of persulfate formed by electrolysis.

2- In case of hydrogen peroxide, potassium chloride (KCl) was used, where 0.025g of the substance was weighed and dissolved in 100ml of distilled water and placed in the device cylinder, and the voltage was set to 1.2 volt for half an hour. The pH of the solution was 5.6. The sample was left after analysis for 24 hours. The next day, 20ml of the analyzed sample was taken, and 1ml of $H_2SO_4$ was added to the sample. The sample was calibrated with a standard solution of potassium permanganate $KMnO_4$ ($0.952 \times 10^{-3}$ M).

## RESULTS AND DISCUSSION

### 1. Water treatment processes

#### 1.1. Electrochemical production of persulfate

Sodium persulfate has been prepared by direct electrolysis of an aqueous solution of sodium sulfate as a starting solution (**Bashir *et al*., 2017; Chaplin, 2019**). The cell consists of a platinum anode and a graphite cathode. The persulfate ions were generated at the anode according to Eq. (10). To evaluate the amount of persulfate formed in the electrolysis solution, a starch-titration process was performed depending on the oxidizing properties of persulfate, which turn iodide ions to iodine as shown in the equation:

$$S_2O_8^{2-} + 2I^- \rightarrow 2SO_4^{2-} + I_2 \qquad (11)$$

At the end of the titration, the liberated iodine was titrated with a standard solution of sodium thiosulfate, eq. (12):

$$I_2 + 2S_2O_3^{2-} \rightarrow S_4O_6^{2-} + 2I^- \qquad (12)$$

The oxidation reaction has a large negative potential (-2.05 volts) and theoretically cannot compete with the oxidation of water (-1.23 volt). However, higher potentials (2.0 and 2.5 V) were applied. The relation between electrochemical generated sodium persulfate concentrations (M) and initial concentrations of sodium thiosulfate (%) for Rod El-Farag station in different seasons, applying potential differences 2.0 and 2.5V, are shown in Figs. (2, 3), respectively. By comparing the results in Figs. (2, 3), it could be noticed that, the amount of persulfate generated in the solution increases with the increase of the initial sodium sulfate added in case of using 2.0 as applied potential during all seasons. Possible explanation might be that the formed thiosulfate radicals have more reactive surface area, which may adhere to algal cell surface and promote the cell coagulation (**Wei *et al*., 2023**). **Yang *et al*. (2022)** reported that, the addition of small amount of peroxymonosulfate increase the efficiency of algal removing by 18%, and with their simultaneous addition, the removal of algae increased to about 97%.

_____

Additionally, some natural organic matter in water can activate thiosulfate to produce $SO_4^{\cdot-}$ (**Srithep & Phattarapattamawong, 2017**). Rapid reaction of $SO_4^{\cdot-}$ with $H_2O$ and its low rate of production, adding to its rapid reaction at neutral pH lead to a weak $HO^{\cdot}$ signal, and this may play an important role in algal removal (**Yang *et al.*, 2022**). In case of using a potential difference of 2.0 volts which is higher than that in the case of 2.5 volts, the volume increases with the increase in sodium sulfate content from 2.5% to 10.0%. This result indicates that the suitable potential for maximum production of persulfate is 2.0 volts.
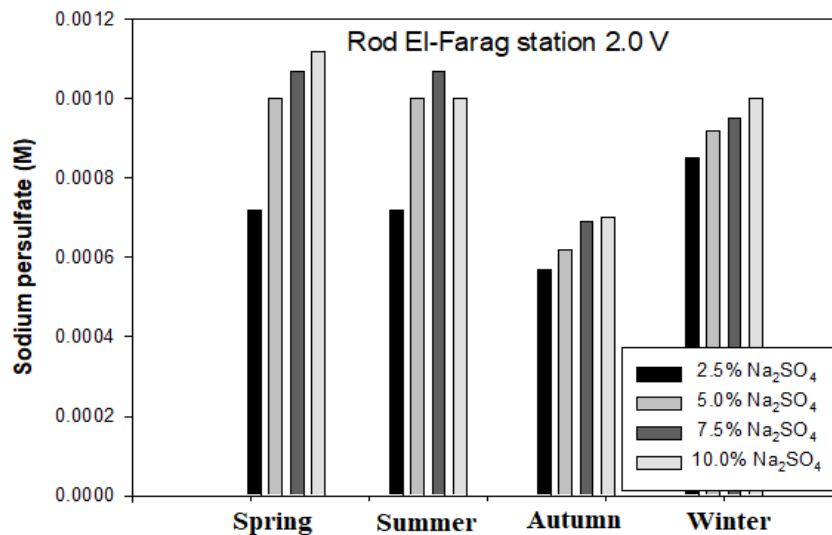


**Fig. 2.** Relation between electrochemical generated sodium persulfate and initial content of sodium sulfate in different seasons for Rod El-Farag station (2.0 V)
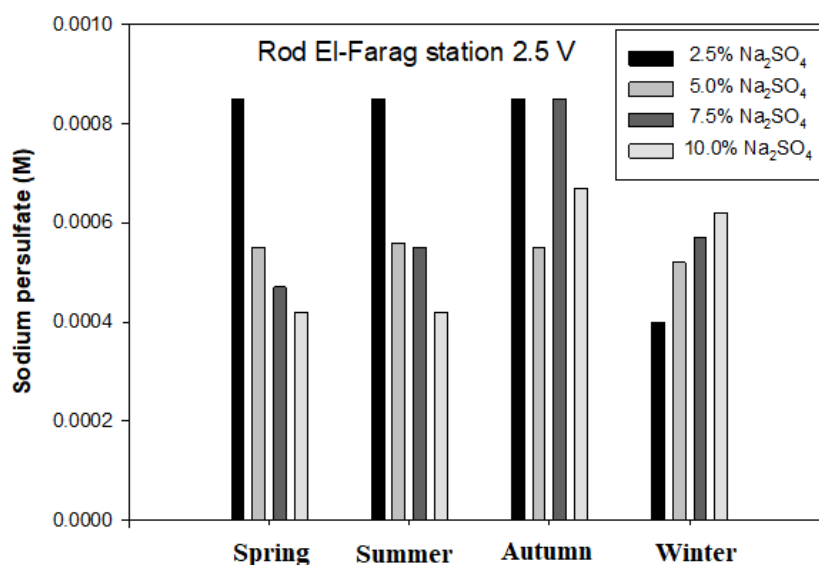


**Fig. 3.** Relation between electrochemical generated sodium persulfate and initial content of sodium sulfate during different seasons for Rod El-Farag station (2.5 V)

## 1.2. Electrochemical production of hydrogen peroxide

Electrochemical hydrogen peroxide synthesis using two-electron oxygen electrochemistry is an intriguing alternative to currently dominating environmentally unfriendly and potentially hazardous anthraquinone process and noble metals catalyzed direct synthesis. Electrocatalytic two-electron oxygen reduction reaction (ORR) and water oxidation reaction (WOR) are the source of electrochemical hydrogen peroxide generation. Various electrocatalysts have been used for the same target and were characterized using several electroanalytical, chemical, spectroscopic and chromatographic tools. Despite the existence of few reviews summarizing the recent developments in this field, none of them has unified the approaches in catalysts' design, criticized the ambiguities and flaws in the methods of evaluation or emphasized the role of electrolyte engineering. Hence, we dedicated this review to discuss the recent trends in the catalysts' design, performance optimization, evaluation perspectives and their appropriateness and opportunities with electrolyte engineering. In addition, particularized discussions on fundamental oxygen electrochemistry, additional methods for precise screening, and the role of solution chemistry of synthesized hydrogen peroxide were presented. Thus, this review disclosed the state-of-the-art in an unpresented view, highlighting the challenges, opportunities and alternative perspectives.

## 2. Treatment of raw water by persulfate and hydrogen peroxide
### 2.1. Removal of chemical pollution

The main physicochemical parameters of the collected water samples were determined before and after treatment. The results in Table (1) show that some parameters are nearly the same for the two seasons, whereas some others such as turbidity, bicarbonate content, COD, oil and grease are quite different from season to another.

### 2.2. Removal of algae and chlorophyll from raw water

Concerning the algal population from the collected samples, it was found that, the highest algal count was observed in autumn and decreased by increasing the temperature to reach its lowest populations during summer (Table 2). In this context, **Shen *et al*. (2011)** elucidated that, the total algal biomass reaches the highest value with the decrease in water temperature, and added that, the concentration of algae cells decreases gradually with the increase in water temperature. The same results are those recorded in the study of **Mohamed *et al*. (2020)** conducted on the River Nile water.

After counting the algal content and the total amount of chlorophyll, the water samples were treated by electrochemically generated persulfate and hydrogen peroxide. The initial concentrations of $Na_2SO_4$ were 2.5, 5.0, 7.5 and 10%, and the experiments were performed at 2.0 and 2.5 volts for the samples taken during the four seasons.

**Table 1.** Essential parameters for raw water sampled in spring and winter from Rod El-Farag station

| Parameter | Season | Raw water | After $Na_2S_2O_8$ (10%) treatment | After $H_2O_2$ treatment |
|---|---|---|---|---|
| **pH** | Spring | 8.27 | 2.7 | 6.9 |
| | Winter | 7.7 | 2.7 | 6.6 |
| **Turbidity (NUT)** | Spring | 10.20 | 8.4 | 3.3 |
| | Winter | 2.03 | 10.3 | 7.4 |
| **Electrical conductivity (mS/cm)** | Spring | 500 | 84600 | 819 |
| | Winter | 495 | 84600 | 819 |
| **$HCO_3^-$ (mg/L)** | Spring | 95.16 | Nil | 75.4 |
| | Winter | 247.7 | Nil | 93.9 |
| **$SO_4^{2-}$ (mg/L)** | Spring | 64.0 | 39000 | 90.0 |
| | Winter | 65.0 | 39000 | 90.0 |
| **$Cl^-$ (mg/L)** | Spring | 28.5 | 4200. 0 | 134. 8 |
| | Winter | 29.7 | 4200.0 | 135. 8 |
| **DO (mg/L)** | Spring | 9.60 | 0.43 | 8.15 |
| | Winter | 9.62 | 0.43 | 8.15 |
| **$BOD_5$ (mg/L)** | Spring | Nil | Nil | Nil |
| | Winter | 1.8 | 2.4 | 5.2 |
| **COD (mg/L)** | Spring | 354 | 90 | 20 |
| | Winter | 11 | 51 | 20 |
| **Oil & grease (mg/L)** | Spring | 81 | 83 | Nil |
| | Winter | 6 | 8 | Nil |
| **TDS (mg/L)** | Spring | 320 | 65265 | 461.7 |
| | Winter | 341 | 65268 | 461.7 |

**Table 2-a.** Algae and chlorophyll removal from Rod El-Farag station by persulfate (Spring)

| Na$_2$SO$_4$ | Algae count (individual/L) | | | Chlorophyll (mg/L) | | |
|---|---|---|---|---|---|---|
| | Before | After | Removal% | Before | After | Removal% |
| 2.0 V | | | | | | |
| 2.5% | 18480 | 7.2 | 99.96 | 9.07 | 2.03 | 77.61 |
| 5.0% | | 5.6 | 99.97 | | 1.92 | 78.83 |
| 7.5% | | 6.2 | 99.96 | | 2.73 | 69.90 |
| 10.0% | | 3.8 | 99.98 | | 2.46 | 72.87 |
| 2.5 V | | | | | | |
| 2.5% | 18480 | 10.0 | 99.94 | 9.07 | 2.81 | 69.01 |
| 5.0% | | 8.6 | 99.95 | | 2.24 | 75.30 |
| 7.5% | | 9.2 | 99.95 | | 2.75 | 69.68 |
| 10.0% | | 11.4 | 99.93 | | 2.92 | 69.80 |

**Table 2-b.** Algae and chlorophyll removal from Rod El-Farag station by persulfate (Summer)

| Na$_2$SO$_4$ | Algae count (individual/L) | | | Chlorophyll (mg/L) | | |
|---|---|---|---|---|---|---|
| | Before | After | Removal% | Before | After | Removal% |
| 2.0 V | | | | | | |
| 2.5% | 3960 | 9.6 | 99.75 | 9.07 | 1.78 | 80.37 |
| 5.0% | | 18.6 | 99.53 | | 1.93 | 78.72 |
| 7.5% | | 11.6 | 99.70 | | 2.20 | 75.74 |
| 10.0% | | 7.4 | 99.81 | | 4.81 | 46.96 |
| 2.5 V | | | | | | |
| 2.5% | 3960 | 14.8 | 99.62 | 9.07 | 4.53 | 50.05 |
| 5.0% | | 16.4 | 99.58 | | 5.11 | 54.80 |
| 7.5% | | 12.0 | 99.69 | | 5.73 | 56.8 |
| 10.0% | | 10.8 | 99.72 | | 2.24 | 65.00 |

**Table 2-c.** Algae and chlorophyll removal from Rod El-Farag station by persulfate (Autumn)

| Na$_2$SO$_4$ | Algae count (individual/L) | | | Chlorophyll (mg/L) | | |
|---|---|---|---|---|---|---|
| | Before | After | Removal% | Before | After | Removal% |
| | | | 2.0 V | | | |
| 2.5% | 69800 | 19.8 | 99.971 | 13.8 | 3.39 | 75.43 |
| 5.0% | | 12.2 | 99.982 | | 3.32 | 75.94 |
| 7.5% | | 9.0 | 99.987 | | 3.94 | 71.44 |
| 10.0% | | 8.0 | 99.988 | | 6.14 | 55.50 |
| | | | 2.5 V | | | |
| 2.5% | 69800 | 18.6 | 99.973 | 13.8 | 3.39 | 75.43 |
| 5.0% | | 9.2 | 99.986 | | 3.30 | 76.08 |
| 7.5% | | 17.8 | 99.999 | | 4.82 | 65.21 |
| 10.0% | | 13.6 | 99.980 | | 8.92 | 35.36 |

**Table 2-d.** Algae and chlorophyll removal from Rod El-Farag station by persulfate (Winter)

| Na$_2$SO$_4$ | Algae count (individual/L) | | | Chlorophyll (mg/L) | | |
|---|---|---|---|---|---|---|
| | Before | After | Removal% | Before | After | Removal% |
| | | | 2.0 V | | | |
| 2.5% | 10720 | 14.2 | 99.86 | 20.75 | 4.16 | 79.95 |
| 5.0% | | 11.6 | 99.89 | | 1.70 | 91.80 |
| 7.5% | | 9.6 | 99.91 | | 0.60 | 97.11 |
| 10.0% | | 4.4 | 99.96 | | 0.32 | 98.45 |
| | | | 2.5 V | | | |
| 2.5% | 10720 | 13.0 | 99.87 | 20.75 | 3.96 | 80.91 |
| 5.0% | | 21.6 | 99.80 | | 2.51 | 95.18 |
| 7.5% | | 9.8 | 99.91 | | 0.81 | 96.09 |
| 10.0% | | 5.0 | 99.95 | | 0.31 | 98.50 |

The data related to algal removal depending on the initial sodium sulfate concentration are displayed in Fig. (4a, b) for the four seasons using 2.0 and 2.5 volts, as applied potential, respectively.
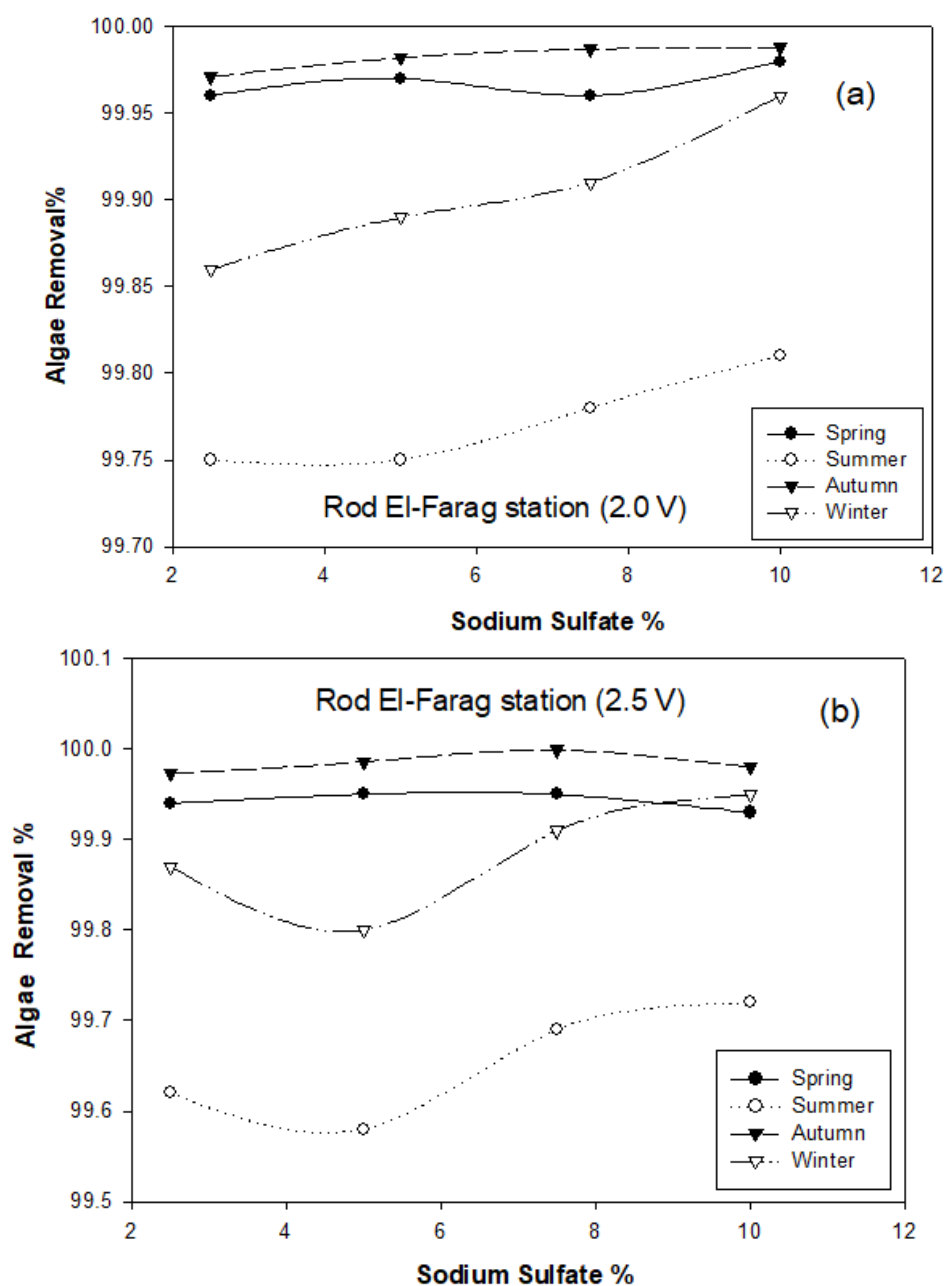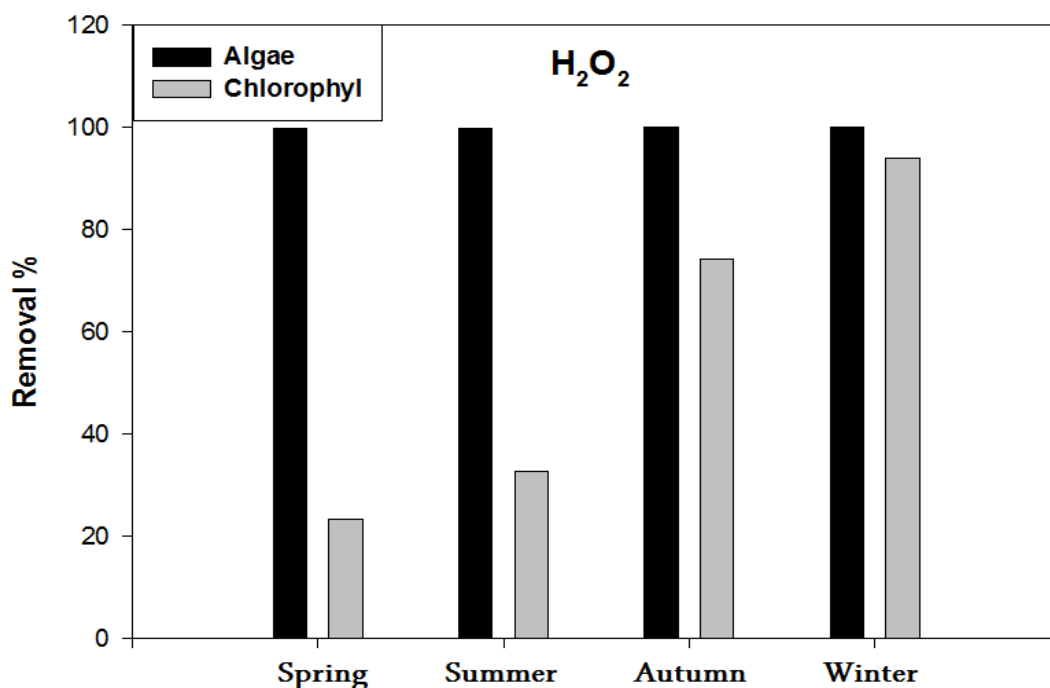
**Fig. 4.** Algal removal efficiency by electrochemical generated sodium persulfate using **(a)** 2.0 and **(b)** 2.5 applied volts

As shown in Fig. (4), the removal efficiency was high at the two potentials and reached its maximum value in autumn and spring.

Table (2) shows that, after treatment with sodium sulfate, the pH value turned to acidic, and this acidic pH favors the formation of radicals, resulting in higher radical oxidation potentials and lower recombination rates. The higher density of those radicals helps in algal degradation process **(Shokoohi *et al*., 2023)**.

When $H_2O_2$ was applied to water samples, the removal efficiency was evaluated for algae and chlorophyll. In case of algae, the removal reached almost about 100% in all seasons, while in case of chlorophyll removal, the efficiency changed from season to season.

Minimum removal was observed in spring (about 23%), while maximum removal was detected in winter (about 92%). These results are shown in Fig. (5). Removal efficiency of $H_2O_2$ may be due to the production of hydroxyl radicals (•OH), which can destroy algal cells, affecting the physiological and biochemical activities of cells, chlorophyll and algae proteins (**Chen *et al.*, 2020**). Moreover, •OH acts as an electrophilic group, which can attack nucleophilic sites in algal organic material, leading to a reduction in organic by-products of algae. The •OH can oxidize algal organic matter to increase the content of methylketone structure, which results in decreasing algal contents (**Wang *et al.*, 2023**). On other hand, •OH primarily destroys macromolecular organic carbon-carbon double bonds and aromatic rings, resulting in the conversion of large molecules to smaller ones, leading to a higher organic matter removal rate (**Yang *et al.*, 2022; Wei *et al.*, 2023**). By increasing the concentration of hydrogen peroxide, the removal efficiency increases (**Mukherjee *et al.*, 2020; Du *et al.*, 2021**).



**Fig. 5.** Removal efficiency of algae and chlorophyll during different seasons using electrochemical generated $H_2O_2$.

## 3. Comparison with other disinfection methods

**Table 3.** A comparison between the results of the efficiency of the present study and other published works in terms of removing algae

| Reagent | Removal efficiency | Reference |
|---|---|---|
| Fe(II)/ peroxymonosulfate | 94.3% | **(Wang *et al.*, 2018**) |
| UV/H$_2$O$_2$ | 94.7% | **(Jia *et al.*, 2018)** |
| H$_2$O$_2$/Fe(II) | 94.0% | (**Zhang *et al.*, 2020**) |
| photo-bioreactor/air flotation | 61% | (**Badawi *et al.*, 2022**) |
|  | Algae | Chlorophyll |
| This study: persulfate | >99.0% | >70.0% |
| This study: ydrogen peroxide | >99.0% | >80.0% |

## CONCLUSION

It could be concluded that, the proposed methods for electrochemical production of water disinfectants are simple and effective for the removal of algae from raw water. The production of sodium persulfate and hydrogen peroxide is easy, fast and cost- effective as the voltage needed for it is very low and could be applied by a solar cell.

## REFERENCES

**Alayande, A. B. and Hong, S.** (2022). Sulfate radical-based advanced oxidation process for algal toxin mineralization in seawater desalination. Desalination, 539-115974.

**Anantharaj, S.; Pitchaimuthu, S. and Noda, S.** (2021). A review on recent developments in electrochemical hydrogen peroxide synthesis with a critical assessment of perspectives and strategies. Advances in Colloid and Interface Science, 287-102331.

**Azarian, G. H.; Mesdaghinia, A. R.; Vaezi, F.; Nabizadeh, R. and Nematollahi, D.** (2007). Algae removal by electro-coagulation process, application for treatment of the effluent from an industrial wastewater treatment plant. Iranian Journal of Public Health, 36(4): 57-64.

**Badawi, A. K.; Ismail, B.; Baaloudj, O. and Abdalla, K. Z.** (2022). Advanced wastewater treatment process using algal photo-bioreactor associated with dissolved-air flotation system: A pilot-scale demonstration. Journal of Water Process Engineering, 46: 102565.

**Bashir, M.; Wei, C.; Aun, N. and Amr, S.** (2017). Electro persulphate oxidation for polishing of biologically treated palm oil mill effluent (POME). J. Environ. Manag., 193: 458–469.

**Bergmann, H.** (2021). Electrochemical disinfection – State of the art and tendencies. Current Opinion in Electrochemistry, 28-100694.

_____

**Bruguera-Casamada, C.; Sirés, I.; Prieto, M. J. and Brillas, E.** (2016). Araujo RM: The ability of electrochemical oxidation with a BDD anode to inactivate Gram-negative and Gram-positive bacteria in low conductivity sulfate medium. Chemosphere, 163: 516–524.

**Chaplin, B. P.** (2019). The prospect of electrochemical technologies advancing worldwide water treatment. Accounts of chemical research, 52(3): 596-604.

**Chen, G.; Ding, X., and Zhou, W.** (2020). Study on ultrasonic treatment for degradation of Microcystins (MCs). Ultrasonics sonochemistry, 63: 104900.

**Chen, S.; Chen, Z.; Siahrostami, S.; Higgins, D.; Nordlund, D.; Sokaras, D., ... and Bao, Z.** (2018). Designing boron nitride islands in carbon materials for efficient electrochemical synthesis of hydrogen peroxide. Journal of the American Chemical Society, 140(25): 7851-7859.

**Collin, F.** (2019). Review Chemical Basis of Reactive Oxygen Species Reactivity and Involvement in Neurodegenerative Diseases. Int. J. Mol. Sci., 20-2407.
comparing the $H_2O_2$/Fe(II) and $H_2O_2$/Fe(III) processes. Science of the Total Environment, 720- 137653.

**Dai, R.; Xiong, Y.; Ma, Y. and Tang, T.** (2020). Algae removal performance of UV-radiation-enhanced coagulation for two representative algal species. Science of the Total Environment, 745-141013.

**Drougi, P.; Elmaleh, S.; Rumeau, M.; Bernard, C. and Rambaud, A.** (2001). Oxidising and Disinfecting by Hydrogen Peroxide Produced in a Two Electrode Cell. Water Res., 35: 3235-3214.

**Du, Z.; Jia, R.; Song, W.; Wang, Y.; Zhang, M.; Pan, Z. and Sun, S.** (2021). The characteristic of N-nitrosodimethylamine precursor release from algal organic matter and degradation performance of $UV/H_2O_2/O_3$ technology, Sci. Total Environ., 795-148739.

**Federation, W. E. and Aph Association** (2005). Standard methods for the examination of water and wastewater. American Public Health Association (APHA): Washington, DC, USA, 21.

**Fernandes, A., Nunes, M. J., Rodrigues, A. S., Pacheco, M. J., Ciríaco, L., & Lopes, A.** (2021). Electro-persulfate processes for the treatment of complex wastewater matrices: Present and future. Molecules, 26(16): 4821.

**Ghernaout, D.** (2017). Microorganisms' electrochemical disinfection phenomena. EC Microbiol, 9: 160–169.

**He, X.; Wu, P.; Wang, S.; Wang, A.; Wang, C. and Ding, P.** (2021). Inactivation of harmful algae using photocatalysts: Mechanisms and performance. Journal of Cleaner Production, 289-125755.

**Jia, P.; Zhou, Y.; Zhang, X.; Zhang, Y. and Dai, R.** (2018). Cyanobacterium removal and control of algal organic matter (AOM) release by $UV/H_2O_2$ pre-oxidation enhanced Fe(II) coagulation, Water Res., 131: 122-130.

**Jung, E.; Shin, H.; Antink, W. H.; Sung, Y. E. and Hyeon, T.** (2020). Recent advances in electrochemical oxygen reduction to $H_2O_2$: catalyst and cell design. ACS Energy Lett, 5: 1881–1892.

**Lara-Ramos, J. A.; Saez, C.; Machuca-Martínez, F. and Rodrigo, M. A.** (2020). Electro-ozonizers: a new approach for an old problem. Sep Purif Technol, 241: 116701.

**Li, Q.; Li, X.; Zhou, C.; Lu, C.; Liu, B. and Wang, G.** (2021). Insight into oxidation and adsorption treatment of algae-laden water: Algal organic matter transformation and removal, Chemical Engineering Journal, 420-129887.

**Martínez-Huitle, C. A. and Brillas, E.** (2008). Electrochemical alternatives for drinking water disinfection. Angew Chem. Int. Ed., 47: 1998–2005.

**Mascia, M.; Vacca, A. and Palmas, S.** (2013). Electrochemical treatment as a pre-oxidative step for algae removal using Chlorella vulgaris as a model organism and BDD anodes. Chemical Engineering Journal, 219: 512-519.

**Mohamed, F.; Nasr El-Deen, F. and Kamal, A.** (2020). The Relationship between Algal Counting and Chemicals Consumption of Conventional Purification Systems at Qena Governorate, Egypt. Egyptian Journal of Aquatic Biology & Fisheries, 24(1): 161–172

**Mohan, H.; Vadivel, S. and Rajendran, S.** (2022). Removal of harmful algae in natural water by semiconductor photocatalysis- A critical review. Chemosphere, 302-134827.

**Mukherjee, A.; Mullick, A.; Teja, R.; Vadthya, P.; Roy, A. and Moulik, S.** (2020). Performance and energetic analysis of hydrodynamic cavitation and potential integration with existing advanced oxidation processes: A case study for real life greywater treatment. Ultrasonics Sonochemistry, 66: 105116.

**Park, Y. M.; Bae, M. K.; Kim, J. W. and Kim, T. G.** (2019). Electrochemical oxidation of high-concentration ozone generation in flowing water through boron doped diamond electrodes. Nanosci Nanotech Lett, 11: 1257–1262.

**Perry, S. C.; Pangotra, D.; Vieira, L.; Csepei, L. I.; Sieber, V.; de León, C. P.; Wang, L. and Walsh, F. C.** (2020). Electrochemical synthesis of hydrogen peroxide from water and oxygen. Nature Reviews Chemistry, 1-25.

**Ren, B.; Weitzel, K. A.; Duan, X.; Nadagouda, M. N. and Dionysiou, D. D.** (2022). A comprehensive review on algae removal and control by coagulation-based processes: mechanism, material, and application. Separation and Purification Technology, 293- 121106.

**Robertson, P. K.; Robertson, J. M. and Bahnemann, D. W.** (2012). Removal of microorganisms and their chemical metabolites from water using semiconductor photocatalysis. Journal of hazardous materials, 211: 161-171

**Round, F. E.; Crawford, R. M. and Mann, D. G.** (1990). The diatoms: biology and morphology of the genera. Cambridge University Press, Cambridge, 747 pp.

**Sathe, P.; Myint, M. T. Z; Dobretsov, S. and Dutta, J.** (2016). Removal and regrowth inhibition of microalgae using visible light photocatalysis with ZnO nanorods: a green technology. Separ. Purif. Technol, 162: 61-67.

**Shafiee, S. A.; Aarons, J. and Hamzah, H. H.** (2019). Erratum: Review—Electroreduction of Peroxodisulfate: A Review of a Complicated Reaction [J. Electrochem. Soc., 165, H785 (2018)]. Journal of The Electrochemical Society, 166(2): X2.

**Shen, Q.; Zhu, J.; Cheng, L.; Zhang, J.; Zhang, Z. and Xu, X. (2011).** Enhanced algae removal by drinking water treatment of chlorination coupled with coagulation, Desalination, 271: 236-240.

**Shokoohi, R.; Rahmani, A.; Asgari, G.; Ashrafi, M. and Ghahramani E.** (2023). Removal of algae using hydrodynamic cavitation, ozonation and oxygen peroxide: Taguchi optimization (case study: Raw water of sanandaj water treatment plant). Process Safety and Environmental Protection, 169: 896–908.

**Sivey, J. D.; McCullough, C. E. and Roberts, A. L.** (2010). Chlorine monoxide ($Cl_2O$) and molecular chlorine ($Cl_2$) as active chlorinating agents in reaction of dimethenamid with aqueous free chlorine. Environ. Sci. Technol, 44: 3357–3362.

**Song, J. and Cho, S. (2020)**. Catalytic materials for efficient electrochemical production of hydrogen peroxide. APL Mater, 8(5).

**Srithep, S. and Phattarapattamawong, S.** (2017). Kinetic removal of haloacetonitrile precursors by photo-based advanced oxidation processes ($UV/H_2O_2$, $UV/O_3$, and $UV/H_2O_2/O_3$). Chemosphere, 176: 25–31,

**Wang ,Y.; Liu, R.; Jia, K.; Song, W. and Jia, J.** (2018). Counter-current/co-current dissolved air flotation (CCDAF) system for algae-laden surface water treatment. Desalin. Water Treat, 130: 37–43.

**Wang, B.; Zhang, Y.; Qin, Y. and Li, H.** (2021). Removal of Microcystis aeruginosa and control of algal organic matter by Fe (II)/peroxymonosulfate pre-oxidation enhanced coagulation. Chemical Engineering Journal, 403: 126381.

**Wang, X.; Wang, X.; Mi, J.; Du, Q.; Wang, Y.; Chen, W., ... and Jia, R.** (2023). $UV/H_2O_2/O_3$ removal efficiency and characterization of algae-derived organic matter and odorous substances. Journal of Environmental Chemical Engineering, 11(1): 109128.

**Wei, J.; Shi, L. and Wu, X.** (2023). Electrochemical advanced oxidation process with simultaneous persulfate and hydrogen peroxide on-site generations for high salinity wastewater. Separation and Purification Technology, 30: 123147.

**Yang, X.; Yao, L.; Wang, Y.; Zhang, X. and Ren, P.** (2022). Simultaneous removal of algae, microcystins and disinfection byproduct precursors by peroxymonosulfate (PMS)-enhanced Fe (III) coagulation. Chemical Engineering Journal, 445: 136689.

**Yu, K. L.; Ong, H. C. and Zaman, H. B.** (2022). Microalgae Biomass as Biofuel and the Green Applications. Energies, 15(19): 7280.

**Zhang, X.; Ma, Y.; Tang, T.; Xiong, Y. and Dai, R.** (2020). Removal of cyanobacteria and control of algal organic matter by simultaneous oxidation and coagulation -

**Zhang, X.; Xi, Y.; Xia, C. and Wang, H.** (2020). Insight into practical scale electrochemical H2O2 synthesis. Trends Chem, 2: 942–953.