

Optimal pH for indirect electrochemical oxidation of isopropyl alcohol with Ru-Ti anode and NaCl electrolyte

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SUMMARY

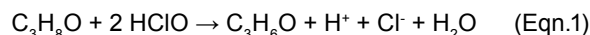
When the levels of human waste exceed an ecosystem's native purification capacity, pollution causes large, long-term damage. Therefore, to prevent wastewater spillage from damaging the environment and raising external cost to the society, industries are required to degrade pollutants in wastewater to an acceptable level according to local regulations before emission. This investigation uses an electrochemical system to degrade isopropanol—a common pollutant found in wastewater—and find the optimal pH level at which the highest degradation of isopropanol takes place. We hypothesized that by decreasing the pH value due to an increase in the amount of HClO (a strong oxidant) in the solution, the degradation of isopropanol (IPA) into acetone should increase. The result supports the hypothesis and shows the electrochemical system under acidic conditions has a higher efficiency than alkaline conditions. Under pH 5–6, NaCl concentration of 2%, initial IPA concentration of 500ppm total organic carbon, and a current of 1 ampere, the electrochemical system degrades 98.6% of IPA into acetone and other intermediate compounds in under 180 minutes. Furthermore, with such a high transfer rate, the system demonstrates its potential to degrade isopropanol to generate acetone, which is a commonly-used agent found in a variety of products ranging from lab cleaning products to nail varnish.

INTRODUCTION

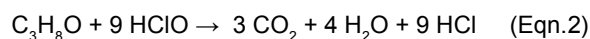
The cost of a single oil spill event can cost society as much as US\$1 billion to clean up (1). Usually, ecosystems are able to absorb waste from human activities (2). However, as the amount of waste continues to increase and exceeds purification capacity, pollution results in large, long-term damage to the ecosystem (2). High-purity isopropyl alcohol (IPA) is mostly used in the semiconductor industry as a cleaning agent for removing residual organic matter on the water surface (3). With increased use of semiconductor-containing devices, the wastewater generated needs to be appropriately cleared of IPA to avoid environmental issues (3). Traditional methods including biological degradation, chemical degradation, and photocatalysis, face problems such as being limited to high initial pollutant concentration, secondary pollution, and low energy and cost efficiency (4). In recent years, electrochemical techniques for treating effluents

containing organic waste have gained much attention and are being studied for application in the process industry (5).

Electrochemistry is the study of the chemical process that causes electrons to transfer from one molecule to another (6). During the process, the element which loses the electron undergoes oxidation, and the element which gains electrons undergoes reduction (6). An electrolytic cell is composed of electrolytes to increase the conductivity of solution, a negative electrode (anode) which reduces compounds in solution, a positive electrode (cathode) which oxidizes compounds in solution, and a power supply providing electrical energy to the system (6). Electrochemical treatment utilizes the electrolytic cell and either oxidizes organic compounds directly with anode, or forms oxidizing agents which then degrade the organic compounds in wastewater (6). Dehydrogenation, for instance, refers to the removal of hydrogen from organic compounds to turn one organic compound into another form (7). IPA was expected to dehydrogenate into acetone by HClO, an oxidizing agent produced in an electrochemical system with NaCl electrolytes, according to the following equation:

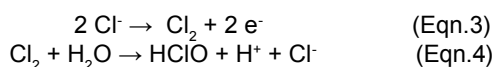


Mineralization of organic compounds refers to when an organic compound is converted to CO_2 , resulting in a reduction of total oxidizing carbon in the solution. Since simply degrading IPA into acetone may lead to further environmental issues regarding the recycling or emission of acetone, mineralization is also a goal which this investigation is looking toward. Equation 2 shows how IPA is completely mineralized by HClO.



Electrochemical treatment provides alternative solutions with the advantage of high cost-efficiency, automatability, and being “environmentally friendly” (8). Drunen *et al.* (2014) used nickel foam electrodes to convert IPA into acetone using a KOH electrolyte solution and current density of 2.6 mA cm^2 , achieving a conversion rate of 5.6 mM per hour. Their investigation demonstrated the capacity of an electrochemical reaction to convert IPA to acetone and demonstrated how variables including current, temperature, and initial concentration of IPA affect IPA degradation (9). Nevertheless, the article did not determine how pH affects the performance of electrochemical systems. In this manuscript, we studied the usage of a metal-mixed oxide (MMO) anode in the electrochemical synthesis of organic compounds under different pH.

Previous researches have shown that MMO electrodes are adaptive to extreme environments and inexpensive, making them suitable for industrial application (5). MMO electrodes use indirect oxidation, meaning some electroactive substances are generated at the anode surface and are used to oxidize organic pollutants. As shown in Equation 3, anode generates the chlorides from dissolved NaCl electrolyte into Cl₂. The Cl₂ will then spread in the bulk of solution through mass transport, forming strong oxidants such as HClO to oxidize organic pollutants, as shown in Equation 4 (10).



Electrochemical systems are convenient in industrial application as they require less space, can treat solutions with high initial concentration of pollutants, and produce less by-product than conventional methods. Also, with strong anodes, the system has the capability to run for a long period of time, saving maintenance and material costs. While indirect electrochemical oxidation is widely applied in decolorization of dyes, there are still limited investigations into the application of this technique to the degradation of IPA (11). Our experiment investigated the possibility of degrading IPA-polluted wastewater using indirect electrochemical treatment by looking into how differing pH affects the removal of low concentrations of IPA (500ppm total organic carbon, TOC). In an acidic environment, the amount of HClO in the solution will increase; therefore, we hypothesized that as the pH of the solution decreases, the removal rate of IPA and acetone will increase (11). The results of this investigation indicated that under pH 5-6, the electrochemical system reaches optimal IPA removal.

RESULTS

In this investigation, we measured the change in concentration of IPA and acetone in the electrochemical system under different pH ranges. Before electrochemical treatment, the pH of the solution was 5. Chlorine ions from NaCl added to the solution were reduced into Cl₂ on the anode according to Equation 3, and then Cl₂ reacted with water to form HClO in solution as shown in Equation 4. The formation of HClO caused the pH of the solution to rise to pH 8-9. As the reaction proceeded, the degradation of IPA to acetone, as shown in Equation 1, produced hydrogen ions and caused the solution to become acidic. To maintain the pH of the solution in a range, as the reaction proceeded, we

Table 1: IPA concentration (mg/L) at each pH range. The measurement of IPA concentration was taken three times, and the average values with error bars presenting the absolute uncertainty of each data point are shown in Figure 2, although for most data points, the absolute values are too small to be clearly seen in the graph.

pH	IPA concentration (mg/L) Δppm = ±0.01mg/L							
	0hr		1hr		2hr		3hr	
	0hr	Percent uncertainty	1hr	Percent uncertainty	2hr	Percent uncertainty	3hr	Percent uncertainty
2-3	710.53	1.48	179.58	4.35	1.94	2.59	1.93	6.22
3-4	680.08	0.69	198.01	3.15	101.67	5.24	71.83	3.40
5-6	605.02	1.26	111.89	4.26	8.94	8.28	8.74	4.12
7-8	773.61	1.69	622.80	1.80	544.09	2.04	488.22	4.68
10-11	580.34	2.25	554.91	2.17	555.31	2.24	540.09	1.88

Table 2: Normalized IPA concentration (mg/L) at each pH range. The data are normalized by dividing each measurement in Table 1 by t = 0 hours. Values are taken to the third decimal place because some values will equal zero if not shown to the third decimal place.

pH	IPA concentration (mg/L) Normalized Value Δppm = ±0.01mg/L			
	0hr	1hr	2hr	3hr
2-3	1.00	0.253	0.003	0.003
3-4	1.00	0.291	0.150	0.106
5-6	1.00	0.185	0.0150	0.014
7-8	1.00	0.805	0.703	0.631
10-11	1.00	0.956	0.957	0.931

adjusted the solution's pH by adding NaOH and H₂SO₄. Each experiment under different pH conditions ran three hours with an NaCl concentration of 2%, a current of 1 ampere, and initial IPA concentration of 500 ppm TOC. Then, we used gas chromatography to measure the concentration of IPA and acetone at 0 hour, 1 hour, 2 hours, and 3 hours.

Table 1 shows the concentrations of IPA in solution after 0 hours, 1 hour, 2 hours, and 3 hours of electrochemical treatment with different pH. **Table 2** shows the normalized value of IPA concentration. Under all pH conditions, the concentration of IPA decreased. We observed a maximum decrease in the concentration of IPA after three hours under pH 2-3 (708.07 ppm) and the minimum decrease under pH 10-11 (40.25 ppm) (**Table 1**). We found that IPA removal was the highest at pH 2-3 with an efficiency of 99.7%, followed by 98.6% at pH 5-6, 89.4% at pH 3-4, 36.9% at pH 7-8, and 6.9% at pH 10-11 (**Figure 1**). The data, after normalization, showed a trend of IPA removal rate with varying pH which suggested the concentration of IPA decreases most rapidly under pH 2-3, followed by pH 5-6 and pH 3-4 over three hours of electrolysis (**Figure 2**). On the other hand, under alkaline conditions, the concentration of IPA decreased much slower.

Besides the concentration of IPA, we also analyzed the acetone concentration with gas chromatography. **Table 3** showed acetone concentrations of the bulk solution at different pH ranges after 0 hours, 1 hour, 2 hours, and 3 hours of electrolysis treatment. Due to different conditions of gas chromatography, the initial values were sometimes negative according to the calibration. The negative value in **Table 3** represented zero ppm of the desired compound, and thus, the percent uncertainty for negative value measurement was

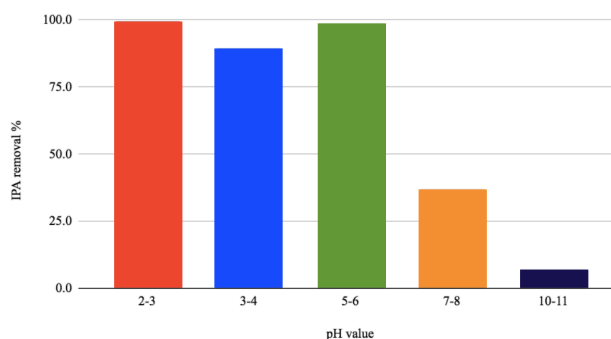


Figure 1: Percent IPA removal in different pH ranges. The normalized removal rate is calculated by dividing the difference between the initial and final concentrations of IPA by the initial concentration of IPA and multiplying by 100.

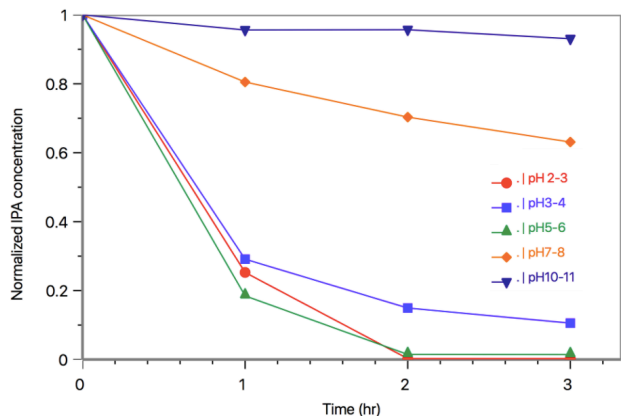


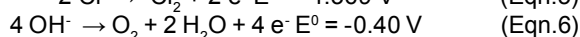
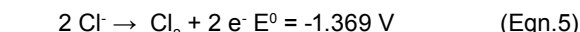
Figure 2: Trend of normalized IPA concentrations at various pH ranges from 2-11. The data are normalized to t = 0 hours in Table 1.

0%. We observed the maximum increase in the concentration of acetone after three hours under pH 5-6 (551.00 ppm), and no formation of acetone under pH 10-11 (Table 1). The investigation indicated that the acetone concentration increases most rapidly under pH 5-6, followed by pH 3-4 and pH 2-3 (Figure 3). Under alkaline conditions, the increase of acetone concentration was much slower.

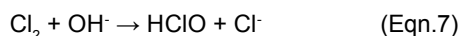
DISCUSSION

Effect of change in pH on the degradation of IPA

Under pH 5-6, NaCl concentration of 2%, and current 1 ampere, the electrochemical system converted 98.6% of IPA into acetone and other intermediate compounds within 180 minutes (Figure 1). The result of the experiment indicated that pH strongly affected the IPA removal rate. In a non-alkaline system, oxidizing water molecules required more energy than oxidizing chloride (12). Therefore, chlorine was more easily produced in an acidic environment. In an alkaline environment, even though both chloride and hydroxide were attracted to the anode, the reaction potential of hydroxide (-0.40V) is relatively high, making chlorine reduction (-1.369V) less likely to occur in an alkaline environment as shown in Equation 5 and Equation 6 (13). This resulted in a lower amount of HClO formation under basic conditions.



Under all pH conditions, activated chlorine would transfer through the bulk solution and initiate a series of reactions. However, the concentration of three forms of activated chlorine (Cl_2 , HClO , and ClO^-) varied at different pH levels (11). From pH 2-6, chlorine reacted with OH^- ions and formed hypochlorous acid according to Equation 7.



At pH 7-11, the excess OH^- caused a different reaction with the hydrogen of HClO and formed another form of activated chlorine, ClO^- , according to Equation 8 (10).

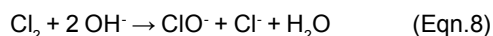
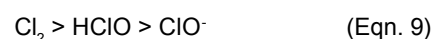


Table 3: Acetone concentration (mg/L) at each pH range. As the initial values were sometimes negative according to the calibration, the negative values in the table can be assumed to be ppm. The measurement of acetone concentration was taken three times, and the average values with error bars presenting the absolute uncertainty of each data point are shown in Figure 3, although for most data points, the absolute values are too small to be clearly seen in the graph.

pH	Acetone concentration (mg/L)							
	$\Delta \text{ppm} = \pm 0.01 \text{ mg/L}$							
	0hr	Percent uncertainty (%)	1hr	Percent uncertainty (%)	2hr	Percent uncertainty (%)	3hr	Percent uncertainty (%)
2-3	-133.78	0.00	368.34	3.48	398.43	1.67	478.46	0.65
3-4	-43.26	4.29	401.56	1.11	493.85	3.42	512.14	1.34
5-6	-7.17	11.01	527.34	0.66	554.22	2.79	551.00	2.72
7-8	2.18	36.24	57.18	4.42	95.43	2.16	109.50	5.15
10-11	-2.52	0.00	-2.52	0.00	-2.52	0.00	-2.52	0.00

At pH 2-3, the proportion of Cl_2 was greatest. At pH 5-6, the proportion of HClO was highest. At pH 7-11, the proportion of ClO^- was highest (10). According to Equation 2, completely mineralizing one mole of IPA required nine moles of HClO .

Therefore, we hypothesized that at pH 5-6, where HClO has the highest concentration, the removal efficiency of IPA both into acetone and mineralization should be the highest. However, the removal percentage of IPA at pH 2-3 was the highest (99.7%) while the removal percentage of IPA at pH 5-6 came second (98.6%) (Figure 1). This phenomenon indicated HClO and Cl_2 were both strong oxidants for IPA oxidation, with Cl_2 showing a slightly stronger oxidizing ability for IPA. In contrast, ClO^- was not a powerful oxidizing agent for IPA oxidation because, at pH 7-10, where the ClO^- concentration was the highest, the degradation efficiency was much lower than in acidic condition (Figure 2). The overall oxidizing power of activated chlorine for IPA was in the following sequence:



Notably, at pH 2-3 the solubility of chlorine decreased and resulted in chlorine gas escaping, raising safety concerns. Thus, for industrial applications, removing IPA at pH 5-6 may

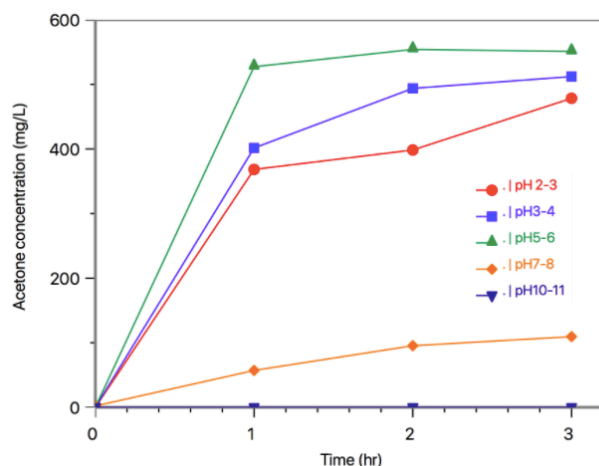
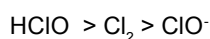


Figure 3: Trend of acetone concentration changes at various pH ranges from 2-11. Each point in the graph represents the average of three technical replicates. The error bars presented in the figure demonstrate variation across technical replicates instead of experimental replicates. All negative values are put at zero.

be a better approach.

Effect of pH on the formation and degradation of acetone

We expected that at a certain pH range, the additional electrical energy in electrochemical oxidation can reach optimal efficiency and overcome the energy barriers of mineralizing IPA into CO₂ instead of acetone in three hours. However, the result showed a lack of evidence of complete mineralization in all of the pH ranges. At pH 7–10, acetone was barely formed because the oxidizing power of ClO⁻ was not enough to degrade IPA into acetone and other by-products. At pH 2-3, 3-4, and 5-6, HClO and Cl₂ degraded IPA into acetone, and **Table 3** and **Figure 3** displayed a clear increase in the concentration of acetone. At pH 2-3 and pH 3-4, the concentration of acetone continued to increase after three hours of electrochemical treatment (**Figure 3**). However, at pH 5-6, the concentration of acetone increased up to 2 hours of treatment and leveled off over the last hour (**Figure 3**). Also, in **Table 3**, there was a slight decrease in acetone concentration (about 3 ppm). This trend indicated that in terms of acetone oxidation, the overall oxidizing power of activated chlorine for acetone was in a different sequence compare to IPA, as shown below:



IPA contains an O-H bond with a bond enthalpy of 460 kJ/mol and acetone has a C=O bond with a bond enthalpy of 745 kJ/mol(14). Because of the high bond enthalpy of the C=O bond, the degradation of acetone requires stronger oxidants with higher oxidizing power or higher selectivity toward the C=O bond. As electrochemical systems are mostly used for degradation of organic compounds, we expected that at certain pH, the acetone could also be degraded into other less harmful organic compounds or mineralized into CO₂. However, the system showed otherwise. Data from **Figure 3** showed that acetone was removed and stopped increasing only under pH 5-6 with the optimal removal of IPA occurring at pH 2-3. These results suggested that the system had a higher selectivity toward IPA than acetone when Cl₂ concentration was higher while showing a stronger affinity for acetone when the HClO concentration was higher. The reason why the system at most pH degraded IPA instead of acetone might be because acetone was already in a more oxidized state, so a stronger oxidant than HClO was needed to convert acetone further. **Table 3** further indicated HClO had limited capability to degrade acetone in our electrochemical system by showing that in all pH ranges besides pH 5-6, the acetone concentration continued to increase after three hours of electrochemical treatment.

Overall, even though this electrochemical system efficiently removed IPA through the production of acetone, the system did not efficiently mineralize this organic compound. Besides oxidizing power, indirect MMO electrochemical oxidation efficiency was also limited by mass transport. As only the chloride ions closest to the anode formed HClO, areas closer to the anode contained the highest concentration of oxidant. Since HClO reacted with nearby organic compounds, the oxidants in high concentration areas barely diffused, causing organic compounds further away from the anode to degrade more slowly, affecting the overall removal efficiency of acetone and IPA.

In terms of industrial application, although the electrochemical system had low capacity in mineralizing IPA, with such a high transfer rate of IPA into acetone, the system was shown to have the capacity to recycle IPA by generating IPA into acetone, which people can re-apply in lab cleaning and in nail varnish.

When using this system, there are two main environmental concerns. First is the production of chlorine ions and chlorine gas during the procedure. Qualitative observation showed that electrochemical treatment produced chlorine gas during the second or third hours in all pH ranges (data not shown). Although the exact amount of chlorine gas was unknown, we expected that the system might contain an amount of chlorine compounds which does not meet the Taiwanese government waste emission standards. Therefore, one future investigation is to examine the amounts of chlorinated compounds produced and to provide a post-treatment method for lowering their levels. A second environmental concern is the large production of acetone. Acetone is considered not hazardous to the environment in low concentrations. However, if all of the IPA in the electrochemical process transforms into acetone, then the solution will contain high concentrations of acetone and harm the organisms in the ecosystem (15). Therefore, in order to apply electrochemical treatment to wastewater emissions, we looked forward to further research into the mineralization of acetone.

We estimated the running cost of the system for industrial application. Oxidizing one mole of IPA into acetone required 2 moles of HClO, and to produce 1 mole of HClO required 1 mole of Cl₂, which required 2 moles of electrons to form. Therefore, to oxidize 1 mole of IPA requires 4 moles of electrons. To degrade 1 kg of IPA required 66.5 mole of electrons, which is 1782.2 A·h. The average voltage during the electrochemical process is 3.6 V, so the total cost of electrical energy to run the system will be 6.4 kW·h. In Taiwan, 1 kW·h costs 3 NTD, hence degrading 1 kg of IPA to acetone requires 19.2 NTD, excluding cost for system setup and maintenance. According to Taiwanese government report, Taiwan generated about 469870 kg of industrial wastewater in 2017, which means the system will cost a minimum of 9,021,504 NTD to degrade this waste (16). This price is still too high for small or medium industries, and we expect future investigation to also look into reducing the running cost.

One error of this investigation is that due to the time limit of the investigation, we only did one trial for each pH variation. Because of the lack of experimental replicates, whether the data collected in this experiment is significant with more trials is unknown. In future investigations on this topic, more trials should be done to verify the accuracy of this experiment and develop a better understanding of the relationship between pH and IPA degradation. In addition, to be applied to industries for the mineralization of organic waste, further optimization of parameters such as flow rate and acetone degradation is needed. Last but not least, this investigation into IPA degradation operated under a set of conditions which may not be applicable in all industrial cases. Therefore, before applying this electrochemical system, specific industries should do running tests to adjust the operation parameters to optimal with assistance from professionals.

MATERIALS AND METHODS

Electrochemical treatment was carried out with three Ru-

Ti anodes and two Ti cathodes connected to a direct current power supply by two wires. The initial volume of solution going through electrochemical treatment was 1 L. All electrochemical experiments were carried out with an initial IPA concentration of 500 ppm TOC and 2% (w/v) NaCl supporting electrolytes. The pH measurement was carried out with an electronic pH meter (SUNTEX INSTRUMENTS CO.,LTD). We calibrated the pH meters with two standard solutions with pH values of 4 and 7 to maintain data accuracy. All sample analyses were carried out using gas chromatography (GC) flame ionization detector (FID). FID ionizes organic compounds into ions, producing a current that was proportional to the carbon mass (17). The current was then collected and displayed as a FID signal versus time graph on the connected computer (17). As GC was sensitive to hydrocarbon impurities, before every experiment, we performed calibration in order to maintain data accuracy (17). GC analysis was carried out with a flow rate of 0.6 mL/min, oven temperature 40°C, injection temperature 40°C, and FID temperature of 280°C, and calibrated using the 4-points method: 50, 100, 500, and 1000 ppm.

The normalized data shown in **Table 2** was calculated by dividing each measurement in **Table 1** by the IPA concentration at 0 hours. The percent uncertainty of the IPA and acetone concentration was calculated by Equation 10 and the percent removal shown in **Figure 1** is calculated by Equation 11 using normalized values. The absolute uncertainty was calculated as the range of data repetitions divided by 2.

$$\frac{\text{Absolute uncertainty}}{\text{Measured value}} \quad (\text{Eqn. 10})$$

$$\frac{\text{Initial concentration of IPA} - \text{Final concentration of IPA}}{\text{Initial concentration of IPA}} \times 100\% \quad (\text{Eqn. 11})$$

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REFERENCES

- Cohen, Mark. "A Taxonomy of Oil Spill Costs—What are the Likely Costs of the Deepwater Horizon Spill." *Resources for the Future*. Web, 2010, media.rff.org/documents/RFF-BCK-Cohen-DHCosts.pdf.
- Jiang, Yu, *et al.* "Economics of social trade-off: Balancing wastewater treatment cost and ecosystem damage." *Journal of Environmental Management*, Vol. 211, 2018, pp. 42–52. DOI:10.1016/j.jenvman.2018.01.047.
- Wu, J, *et al.* "The oxidation study of 2-propanol using ozone-based advanced oxidation processes." *Separation and Purification Technology*, Vol. 62, Issue 1, 2008, pp. 39-46. DOI:10.1016/j.seppur.2007.12.018
- Zhou, Minghua, *et al.* "A comparative experimental study on methyl orange degradation by electrochemical oxidation on BDD and MMO electrodes." *Separation and Purification Technology*, Vol. 78, Issue 3, 2011, pp. 290-297. DOI:10.1016/j.seppur.2011.02.013.
- Saha, Pradip, *et al.* "Removal of organic compounds from cooling tower blowdown by electrochemical oxidation: Role of electrodes and operational parameters." *Chemosphere*, Vol. 259, 2020, pp.127491. DOI:10.1016/j.chemosphere.2020.127491.
- Allen, J. *et al.* (2001). *Electrochemical methods fundamentals and applications*. John Wiley & Sons.
- Hale, Arthur J. "The Manufacture of Chemicals by Electrolysis." *Nature*, Vol 104, 1920. DOI: 10.1038/104529b0
- Shan, Lili, *et al.* "Investigation on decolorization of biologically pretreated cellulosic ethanol wastewater by electrochemical method." *Chemical Engineering Journal*. Vol. 323, 2017, pp. 455-464. DOI: http://dx.doi.org/10.1016/j.cej.2017.04.121
- Drunen, Julia, *et al.* "Journal of Electroanalytical Chemistry", Vol. 716, 2014, pp. 120–128. DOI:10.1016/j.jelechem.2013.08.003
- Martínez-Huitle, Carlos A, *et al.* "Electrochemical oxidation of organic pollutants for wastewater treatment." *Current Opinion in Electrochemistry*. Vol. 11, 2018, pp. 62-71. DOI: 10.1016/j.coelec.2018.07.010
- Maruyama, N. *et al.* "Experimental Investigation on Hypochlorous Acid Water Production using Electrode Plates without a Barrier Membrane (Part I: Production conditions for high-concentration Hypochlorous acid water)." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*. Vol.12, Issue. 5, version. 2, 2015, pp.48-57. DOI: 10.9790/1684-12524857.
- "The Disinfection of Drinking Water." National Research Council (US) Safe Drinking Water Committee. *Drinking Water and Health*. Vol. 2, pp. 5-139. Web. 1980, ncbi.nlm.nih.gov/books/NBK234592/pdf/Bookshelf_NBK234592.pdf
- Vanyšek, P. "Electrochemical series." *Handbook of Chemistry and Physics*. Edition. 91, pp.5-80. Web. 2012, pdfs.semanticscholar.org/d69f/b8901fa978ef52cc489d4cac71bb23da9922.pdf
- Sanderson, R. (2012). *Chemical bonds and bonds energy*. 2nd Edition. Vol. 21. New York: Academic Press.
- Li, Yue, *et al.* "Two coordination polymers with enhanced ligand-centered luminescence and assembly imparted sensing ability for acetone." *Journal of Materials Chemistry A*, Vol. 2, No. 25, 2014, pp. 9469-9473.
- (2018). *Yearbook of Environmental Protection Statistics Republic of China*. Taipei City: Environmental Protection Administration, Executive Yuan.
- Dorman, Frank L. *et al.* "Gas Chromatography." *Analytical Chemistry*, Vol. 82, 2010, pp. 4775–4785. DOI:10.1021/ac101156h.

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