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An Experimental Analysis of Electrolysis: Identifying the Optimal Electrolyte Type and Electrolyte Concentration in Oxyhydrogen Production

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Abstract

The objective of this study is to experiment on the process of electrolysis and identify the optimal electrolyte between Sodium Chloride, Sodium Bicarbonate, and Sodium Hydroxide for oxyhydrogen production. The optimal electrolyte will be identified based on observed bubbling, observed effects on the electrolysis cell and their trend, and the rate of change of the effects for each electrolyte. The experiment was conducted for 45 minutes on each electrolyte, and observations were recorded at 5-minute intervals on a Likert scale. The effects observed and recorded on a Likert scale were foaming, deterioration, and turbidity. The data from the Likert scale was then treated using Mann-Kendall and Sen's Slope statistical treatment, and based on the analyzed and contextualized data, the researchers concluded that Sodium Hydroxide is the optimal electrolyte to use in electrolysis for oxyhydrogen production. As it had the highest conductivity, the most bubbling, and the second least negative effects observed amongst the three electrolytes tested.

KEYWORDS: Electrolysis, Oxyhydrogen, Sodium Hydroxide, Sodium Chloride, Sodium Bicarbonate.

1. Introduction

Oxyhydrogen, commonly referred to as HHO or Brown's gas, is produced via water electrolysis— a process in which water is split into its integral gases, hydrogen (H_2) and oxygen (O_2), by an electrical current run through the water. With the increase in air pollution worldwide, oxyhydrogen is proposed as a promising alternative energy source because of its many advantages over fossil fuels (Mousa et al., 2024).

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Unlike fossil fuels, oxyhydrogen combustion only produces water vapor, thereby reducing harmful emissions. Additionally, the high flame temperature associated with oxyhydrogen gas makes it suitable for applications requiring intense heat, while its on-demand production capability reduces waste and storage-related risks associated with its explosive nature.

Water electrolysis in itself is a renewable and sustainable chemical energy production method (Şahin, 2024). The process relies on two vital key components: electrodes and electrolytes. The electrodes, commonly containing an anode and a cathode, facilitate the flow of electric current through the water, while the electrolyte, by increasing the ionic concentration, improves the water's conductivity. This is important because the ability of pure water to conduct electricity is said to be very bad due to its lack of minerals and ions (BYJU'S, n.d.). Although the efficiency of electrolysis is not solely reliant on the electrolyte, the electrolyte concentration is a crucial parameter. An optimal concentration ensures effective conduction due to it supplying sufficient ion concentration without introducing excessive viscosity or unwanted side reactions, which can change the ohmic resistance and overall reduce the efficiency. (Slama, 2013; Sun, 2018).

Despite the promising potential, oxyhydrogen production is still in the experimental stage, and several challenges remain unresolved. Among these challenges are the high energy input required in comparison to the low energy released upon combustion, issues related to safe storage, and electrode corrosion. Tackling these challenges is crucial for advancing oxyhydrogen as a usable alternative source of energy. Previous studies showed promising results in specific applications, such as improving internal combustion engine performance (Caico, 2020) and enhancing coal powder combustion (Cui et al., 2024). Nonetheless, there is a research gap regarding the optimization of the electrolyte concentration and the selection of the optimal electrolyte to maximize conductivity and oxyhydrogen gas yield.

This study aimed to identify the optimal electrolyte concentration and determine the optimal electrolyte for electrolysis. This investigation (1) established the conductivity for various electrolytes at different concentrations, (2) observed the production speed and determined which electrolyte produces the most oxyhydrogen in the shortest period of time, and (3) documented any associated side effects, such as electrode corrosion. This research's findings are expected to benefit hydrologists, automotive engineers, environmentalists, car manufacturers, hydrogen fuel consumers, and future researchers by improving the efficiency and safety of oxyhydrogen production, thereby advancing renewable energy.

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Conceptual Framework

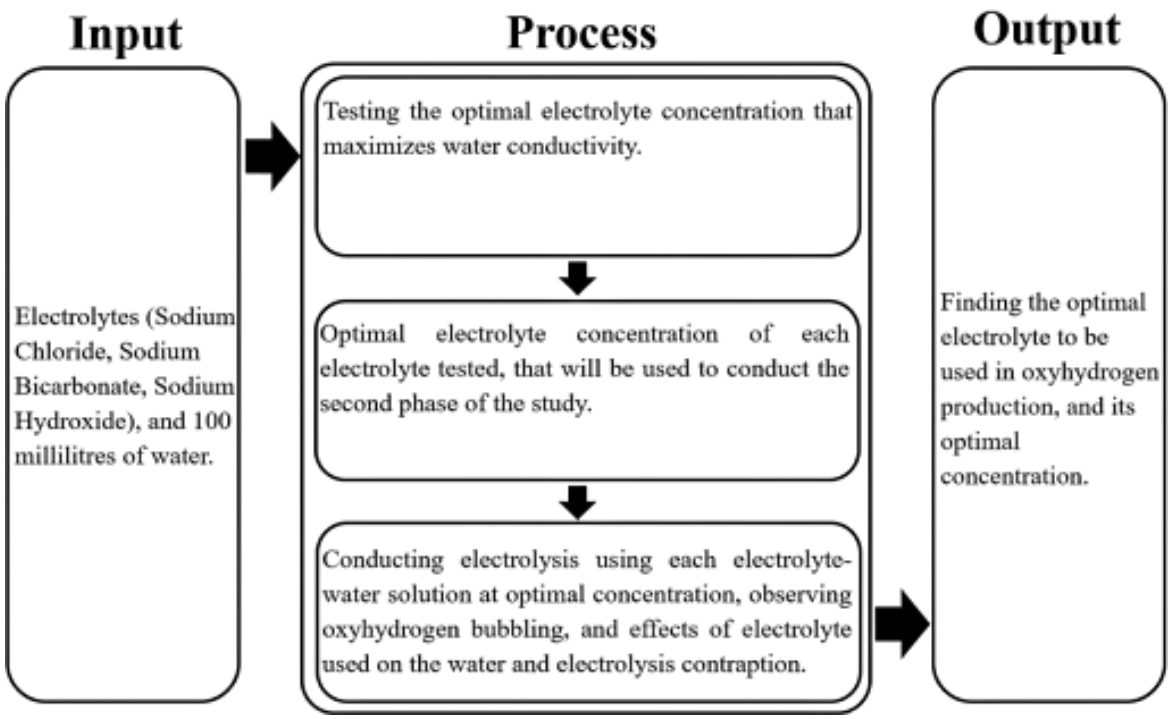

Figure 1. IPO Diagram of Conceptual Framework

The figure above is the theoretical framework of this study, the input-process-output (IPO) framework, which was used as a guide in conducting the experiments.

This study's input consisted of the different electrolytes—sodium chloride, sodium bicarbonate, and sodium hydroxide—along with 100 millilitres of water. The process involved three steps which are testing different electrolyte concentrations to determine which concentration maximizes water conductivity for each electrolyte, determining the optimal electrolyte concentration for each electrolyte tested, and the results were then used in the second phase of this study, and lastly, electrolysis was done using each type of electrolyte and its optimal electrolyte concentration to observe oxyhydrogen bubbling, as well as note any observed effects on the water and electrolysis setup. The output of the study was to find the significant difference between each electrolyte and determine the optimal electrolyte to be used in electrolysis for oxyhydrogen production.

Research Questions

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This study aims to identify the optimal electrolyte to utilize for oxyhydrogen production in electrolysis through the following questions:

1. What is the optimal electrolyte concentration that maximizes the electrical conductivity of water for each electrolyte type?
2. What is the observed oxyhydrogen bubbling for each type of electrolyte at the identified optimal conductivity?
3. What are the observable effects and their trend during the electrolysis process on the water and experimental apparatus of each electrolyte?
4. What is the rate of change of the trends observed during the time series?

Hypothesis

The study tested the following null hypotheses:

1. There are no significant increasing trends observed while conducting electrolysis.
2. There is no significance in the effects' rate of change on each electrolyte.

2. Review of Related Literature

The article from SenzaHydrogen titled "Hydrogen Production From Electrolysis" Focuses on hydrogen production, mainly Proton Exchange Membrane (PEM) water electrolysis. PEM electrolyzers replace alkaline liquid electrolytes with solid polymer electrolytes, eliminating issues like corrosion and inefficiency. The use of a proton exchange membrane allows for proton conduction and gas separation, while the zero-gap structure reduces ohmic resistance, enhancing performance. PEM electrolyzers operate at high current densities (over 1 A/cm^2), making them more efficient than alkaline systems. A challenge found in PEM electrolysis is polarization, which increases the required voltage amount for electrolysis, going above the theoretical minimum. Polarization includes activation, ohmic, and concentration components, with the oxygen evolution reaction at the anode being particularly inefficient due to high polarization. Electrochemical polarization is tied to catalyst activity, and improving catalysts and electrode interfaces can mitigate this. However, the need for expensive noble metals like iridium (Ir) and ruthenium (Ru) for oxygen evolution catalysts, and platinum (Pt) for hydrogen evolution, drives up costs. Reducing the loading of these materials is critical for cost reduction. Ohmic polarization, primarily from membrane resistance, can be lowered by using thinner membranes, though this must balance gas permeation and durability. Concentration polarization, related to water supply and gas removal, depends on the design of the diffusion layer and flow field. Titanium-based materials with corrosion-resistant treatments are commonly used for diffusion layers, but they contribute to the high cost of PEM systems.

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Furthermore, this article from StackExchange titled, “Is there an electrolyte that will halt the production of Hydrogen in water electrolysis?“ 2015 is about water electrolysis and discusses the production of hydrogen gas during the electrolysis of water. The production of hydrogen gas during the electrolysis of water is discussed. Care must be taken in selecting the electrolyte, as an anion from the electrolyte competes with hydroxide ions to release electrons. If the anion has a lower standard electrode potential than hydroxide, it will be oxidized instead of hydroxide, and no oxygen gas will be produced. Similarly, if a cation has a higher standard electrode potential than the hydrogen ion, it will be reduced instead of the hydrogen ion, and no hydrogen gas will be produced.

With that being said, to develop an oxyhydrogen gas generator from a dry cell type with high energy-conversion efficiency, oxyhydrogen (HHO) gas is a promising alternative fuel with several advantages over fossil fuels. These advantages include; High flammability, an improved amount of oxygen, accelerated burning rate, and zero carbon in comparison with fossil fuels. Within the range of tested potassium hydroxide (KOH) concentrations (0.05 to 0.20 M) and applied voltages (10.5 to 13.0 V), the results demonstrated a significant increase in HHO gas production rate with higher applied voltages and electrolyte solution concentrations. It was also observed that the power consumption for HHO gas production increased notably with increasing applied voltage and electrolyte concentration. Furthermore, an increase in applied electrolyte concentration and voltage led to a corresponding rise in temperature. From this study, the optimum conditions for producing HHO gas ranged from 11.5 to 12 V for voltage and from 0.05 to 0.10 M for KOH concentration according to the lowest specific energy and highest HHO gas generator efficiency. Under the previous optimum conditions, the highest productivity, specific energy, and efficiency of the HHO gas generator were 343.9 cm3 min−1, 3.43 kW h m−3, and 53.79%, respectively, using 12.0 V for applied voltage and 0.10 M for electrolyte solution concentration (Mousa, A.M., Sayed, H.A.A., Ali, K.A.M. *et al. “*Energy-conversion efficiency for producing oxyhydrogen gas using a simple generator based on water electrolysis” 2024).

Consequently, in maintaining hydrogen generators, this article recommends using electrolytes. As water is a non-conductor, electrolytes or chemicals increase current flow to a usable rate. A minimum of 95% water purity is recommended. Sodium Hydroxide NaOH, also called “lye,” is a very efficient electrolyte, with the traits of being highly conductive and caustic. Pure sodium hydroxide is available in pellets, flakes, granules, and as a 50% saturated solution, dissolved in water. NaOH is available at industrial chemical suppliers, internet retailers, hardware stores, and agriculture stores. Potassium Hydroxide KOH is the most efficient of the commonly used electrolytes, available from online chemical distribution centers (HHO-1 “Maintenance of Hydrogen Generators. Water and Electricity Consumption”, 2025).

The research by Kumar titled "Hydrogen production by PEM water electrolysis" 2019 showcases the several traits and factors of water electrolysis and its different types. It is stated that hydrogen is one of the most promising clean and sustainable energy carriers and emits only water as a byproduct without any carbon emissions. Hydrogen has many attractive properties as an energy carrier, and high energy density (140 MJ/kg), which is more than two times higher than typical solid fuels (50 MJ/kg). Water electrolysis can be classified into four types based on electrolyte, operating conditions, and ionic agents (OH^-, H^+, O^{2-}): alkaline water electrolysis (AWE), solid oxide electrolysis (SOE), microbial electrolysis cells (MEC), and proton exchange membrane (PEM) water electrolysis. Among these, PEM water electrolysis stands out for its ability to convert renewable energy into high-purity hydrogen. PEM water electrolysis can offer several advantages, such as a compact design, high current density (above 2 A cm^{-2}), high efficiency, rapid response, and operation at low temperatures (20–80 °C). It produces ultrapure hydrogen and oxygen as a byproduct, making it highly suitable for industrial applications. However, the

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reliance on noble metal electrocatalysts—such as Pt/Pd for the hydrogen evolution reaction (HER) and IrO_2/RuO_2 for the oxygen evolution reaction (OER)—makes PEM systems more expensive than alternatives like alkaline electrolysis. Reducing production costs while maintaining efficiency remains a key challenge. The research highlights recent advancements in PEM water electrolysis, particularly in developing efficient and stable HER and OER electrocatalysts. Significant progress has been made in creating electrocatalysts that perform well at high current densities, improving both activity and durability. These developments enable an advancement in PEM water electrolysis toward commercial viability.

From this, the variety of water electrolyzer types and their role in hydrogen production as a renewable energy source. The main electrolysis types, namely alkaline water electrolysis (AWE), polymer electrolyte membrane electrolysis (PEM/SPE), anion exchange membrane electrolysis (AEM), and steam electrolysis (HTEL/SOEL), are considered. Comparisons among these electrolyzer types, including alkaline, PEM-type, anion exchange membranes, and high-temperature electrolysis, are discussed in terms of advantages and disadvantages. An advantage of producing hydrogen via water electrolysis is that it yields more than 99.9% purity compared to other methods. The research also investigates industrial applications and the future potential of water electrolysis processes as mentioned (Şahin, "An Overview of Different Water Electrolyzer Types for Hydrogen Production", 2024).

Furthermore, the effects of various electrolyte types on electrolysis performance. It was shown that wastewater electrolysis can allow the same or an even greater performance in comparison to pure water, as it contains hydrogen-producing bacteria. The electrolytes will lean toward wastewater deemed by their richness in bacteria, which are the basis for hydrogen production, to reach the best production while requiring less power consumption. It was stated that hydrogen production by water electrolysis can be economically viable by using electrical energy from renewable sources such as photovoltaic solar energy. The following wastewater includes: ONAS (municipal wastewater), ammonia water from ammonia production plants, and water with vinegar and urine deemed rich in nitrogenous matter (ammonia). The study found that the addition of NaCl in the electrolytes activated the electrochemical reactions and produced more hydrogen. Furthermore, according to the type of used electrolyte (tap water, margine, gas liquor, wastewater from cooking, puckered olive, urine, the vinegar of pink, municipal wastewater, and finally milk water), there is a variation in the hydrogen flow rate produced by supplying the electrolyzers in electrical current by the photovoltaic module (Slama, "Production of Hydrogen by Electrolysis of Water: Effects of the Electrolyte Type on the Electrolysis Performances" 2013).

Additionally, important parameters affecting hydrogen production include the reacting voltage, the electrolysis temperature (between 25℃ - 250℃), and the operating pressure (between 1 atm -100 atm). The voltage, operating temperature, and the amount of hydrogen produced by electrolysis can be predicted from the temperature, pressure, and the relationship between the reactant and enthalpy. In this study, two electrolyte solutions with different pHs were tested: one was a sulfuric acid solution, and the other was a potassium hydroxide solution, with varied electrolyte concentrations. There was an optimized parameter with different concentrations at the anode and cathode. The electrolysis efficiency was better when the voltage was fixed at 2 volts, and the potassium hydroxide solution concentration was 25 wt% —weight of the solution to the weight of the solvent— at the anode and 30 wt% at the cathode. The reason for this phenomenon was that hydroxide ions cannot pass through the proton exchange membrane. However, hydroxyl ions gradually saturated the anode, so the concentration at the anode was in excess of 25 wt%, at which point the conductivity had a negative tendency. When the sulfuric acid solution concentration was higher at the cathode than at the anode, the ion diffusion effect became significant, leading to the transmission of hydrogen ions through the proton exchange membrane at the

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cathode, which then moved to the anode to work continuously for electrolysis. The best case was with 15 wt% H2SO4 at the anode channel and with 20 wt% at the cathode channel. In addition, increasing the difference in concentration of the sulfuric acid had an effect on the diffusion. In the experiments, increasing the difference in concentration of the sulfuric acid had an effect on the diffusion, fulfilling the purpose of the study; Increasing electrolyzer efficiency without the addition of energy (Cheng-Wei Sun and Shu-San Hsiau, Dept. of Mechanical Engineering, National Central University, 2018).

Moreover, in the use of alkaline electrolytes such as potassium hydroxide and sodium hydroxide during the process of electrolysis, a concentration of one to two grams per liter of distilled water was recommended. The concentration should typically be in the range of 20% to 30% of the water's weight. In comparison to other electrolyzers such as PEM (Proton Exchange Membrane) and SOE (Solid Oxide Electrolyzer), alkaline electrolyzers perform less efficiently but have a low cost and are widely commercialized, yet still have high conductivity and stability. Many other factors affect the efficiency of oxyhydrogen production, such as current density, electrode material, and distance between electrodes which can lead to higher oxyhydrogen gas yields (Yusof et al, "Oxyhydrogen gas production by alkaline water electrolysis and the effectiveness on the engine performance and gas emissions in an IC engine: A mini-review", 2022).

Finally, higher electrolyte concentration leads to an increased hydrogen production rate (HPR), as ionic conductivity improves. However, the study also noted that electrolysis efficiency does not always increase proportionally with electrolyte concentration, suggesting an optimal concentration range for maximum efficiency. Research on single-salt and double-salt electrolytes has provided insights into the role of ionic compositions. Studies indicate that double-salt electrolytes, such as NaCl and $MgCl_2$, enhance HPR more significantly than single-salt electrolytes. This effect is ascribed to increased ionic mobility, which allows faster charge transfer during electrolysis. In conclusion, both single-salt and double-salt electrolytes show a direct relation to HPR, but efficiency shows an inverse relation with voltage with both electrolytes. The inverse relation between voltage and efficiency is due to the resistance of the electrolyte concentration and changes in the voltage of electrodes due to concentration polarization (D. Buddhi, Renewable and Sustainable Energy, R.L. Sawhney, TERI University, and Richa Kothari, Central University of Jammu, 2006).

In summary, previous research studied various electrolysis methods, highlighting their advantages and drawbacks. Research emphasized the role of electrolytes in enhancing electrochemical reactions, noting that competing ions can reduce gas production efficiency. Factors such as voltage, temperature, and electrolyte concentration influence electrolysis efficiency; however, higher concentrations may lead to inefficiencies. Sodium hydroxide (NaOH) is often recommended due to its high conductivity and availability. Nonetheless, these researchers did not discuss the optimal conditions for NaOH, NaHCO3, and NaCl, which this research aims to find.

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3. Methodology

Research Design

This study adopted a quantitative experimental research design, where numerical values and observations were collected and analyzed to identify the optimal electrolyte concentration that maximizes conductivity. Once the said concentration was determined, it was applied in the electrolysis experiment to evaluate any significant differences in oxyhydrogen production among the several types of electrolytes.

Materials and Instruments

This experimental research study utilized the following materials to conduct the experiment:

Table 1
Materials

Tape	Bench Power Supply
Well-Sourced Bottled Drinking Water	Graphite Rod Electrodes
Sodium Hydroxide	1 Liter glass Container
Sodium Bicarbonate	Electric Conductivity Meter
Sodium Chloride	Rubber Filling
Copper Wires	Plastic Boards

Data Gathering Procedure

A. Adding Electrolyte to Water Sample

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1. Make sure weighing scales are calibrated.
2. Use a weighing scale to measure the amount of electrolyte added.
3. Initially, add the recommended concentration (30% of the water's weight) of the electrolyte based on related studies and experiments.
4. Increase and decrease concentration at 5-gram intervals.

B. Testing Conductivity of Electrolyte Concentrations

1. Calibrate the EC meter before use.
2. Test conductivity at every interval using the EC Meter.
3. Record the concentration where the conductivity is at its highest.

C. Electrolysis

1. The researchers conducted one test for each electrolyte type at the optimal concentration that ran for 45 minutes.
2. The electrolysis cell containing water utilized the following electrolytes at optimal concentration:
    a. Sodium Chloride.
    b. Sodium Bicarbonate.
    c. Sodium Hydroxide.
3. To start the electrolysis process, the water was subjected to electricity using a bench power supply with 4 Volts.

D. Measuring Each Sample

1. To measure the observed oxyhydrogen bubbling for each electrolyte type, a mobile phone was used to record the electrolysis process.
2. The observed oxyhydrogen bubbling was measured by comparing the three electrolytes and noting down which one had the most bubbling.
3. The effects on the experimental setup were taken into consideration in evaluating the electrolytes, and were recorded at 5-minute intervals on a Likert scale.

Data Analysis

This research study utilized Mann–Kendall test and subsequently Sen's Slope Estimator to gather and analyze the experimental data. The Mann-Kendall test is a nonparametric method for testing whether there is a consistent

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increasing or decreasing trend in the time series without assuming any particular distribution of the data. Sen's Slope Estimator is a statistical analysis that complements the Mann-Kendall test by quantifying the magnitude of that trend as the median of all pairwise slopes between observations.

4. Results and Discussion

Table 1. Water Conductivity Level of Each Electrolyte at Different Concentrations in Microsiemens

Number of Grams	Sodium Chloride	Sodium Bicarbonate	Sodium Hydroxide
5 g	10.87 µS	1.89 µS	434.78 µS
7 g	11.11 µS	2.22 µS	277.78 µS
10 g	20.00 µS	Did not Dissolve	78.43 µS
15 g	17.76 µS	Did not Dissolve	58.69 µS
20 g	16.69 µS	Did not Dissolve	62.98 µS
25 g	13.12 µS	Did not Dissolve	12.09 µS

Table 1 introduces the different water conductivity levels of each electrolyte at different concentrations, which are measured using microsiemens. There are a total of 3 electrolyte types used in this study: Sodium Chloride, Sodium Bicarbonate, and Sodium Hydroxide. Each of the electrolyte types had concentration levels ranging from 5, 7, 10, 15, 20, and 25 grams per 100 millilitres of water. At the concentration level of 5 grams, Sodium Chloride had a conductivity of 10.87 µS, Sodium Bicarbonate had 1.89 µS, and 434.78 µS for Sodium Hydroxide. At the concentration level of 7 grams, Sodium Chloride had a conductivity reading of 11.11 µS, Sodium Bicarbonate had 2.22 µS, and 277.78 µS on Sodium Hydroxide. Furthermore, the rest of the conductivity levels of Sodium Bicarbonate were not measured due to it not dissolving in the water, as its solubility is very low, so Sodium Bicarbonate will not be mentioned further in the conductivity results. At the concentration level of 10 grams, Sodium Chloride had a reading of 20.00 µS, while Sodium Hydroxide had a reading of 78.43 µS. At the concentration level of 15 grams, Sodium Chloride had a conductivity reading of 17.76 µS, while Sodium Hydroxide had a reading of 58.69 µS. At the concentration level of 20 grams, Sodium Chloride had a reading of 16.69 µS, while Sodium Hydroxide had a reading of 62.98 µS. Last but not least, at 25 grams concentration, Sodium Chloride showed a reading of 13.12 µS, while Sodium Hydroxide showed 12.09 µS. Sodium Chloride had the highest conductivity level at 10 grams, while its lowest conductivity was at 5 grams concentration. Sodium Bicarbonate showed its highest conductivity level at 7 grams, while the lowest was at 5 grams concentration. Sodium Bicarbonate also showed unusual results with the electrolyte not dissolving into the water at 10, 15, 20, and 25 grams. Lastly, Sodium Hydroxide showed the highest conductivity at 5 grams, while the lowest conductivity was recorded at 25 grams.

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The data in Table 3 exhibit distinct trends in the conductivity of the three electrolytes: Sodium Chloride, Sodium Bicarbonate, and Sodium Hydroxide in varying concentrations (5g to 25g per 100 ml of water). Sodium Hydroxide exhibited the highest conductivity at low concentrations, yet showed the lowest conductivity at high concentrations. This suggests that Sodium Hydroxide is a strong electrolyte at low concentrations, but decreases its effectiveness at higher concentrations, possibly due to ion pairing, saturation, or reduced dissociation (Emerson Automation Solutions, n.d.). Sodium Chloride exhibited moderate conductivity, reaching its peak at the middle level concentration, before gradually decreasing at higher concentrations. Unlike Sodium Hydroxide, Sodium Chloride can maintain measurable conductivity even at high concentrations, suggesting better solubility and ion mobility across a wider range of concentrations (Lee, 2020). Sodium Bicarbonate had extremely low conductivity and failed to dissolve beyond 7g, suggesting very poor solubility in water. This makes Sodium Bicarbonate unsuitable for applications requiring high concentrations (NASA, 2024). For the implications of these findings, Sodium Hydroxide's high conductivity at low concentrations makes it ideal for low-concentration applications (e.g., alkaline batteries, electrolysis), while underperforming at higher concentrations. Sodium Chloride's moderate conductivity makes it a reliable choice for applications requiring consistent ionic conduction (e.g., saline solutions, desalination). Sodium Bicarbonate's poor solubility and low conductivity make it inefficient in electrolyte-dependent systems like electrolysis and high-concentration applications, limiting its use to very dilute systems, such as mild buffering agents, rather than conductive applications. The observed reduction in conductivity at higher concentrations (observed from Sodium Chloride and Sodium Hydroxide) likely results from ion-ion interactions, reduced dissociation efficiency, or increased solution viscosity, which holds back ion mobility. While Sodium Hydroxide offers the highest initial conductivity, Sodium Chloride provides more stable performance, and Sodium Bicarbonate is limited by solubility restrictions.

Table 2. Observed oxyhydrogen bubbling of each electrolyte at optimal conductivity

Electrolyte	Oxyhydrogen Production Speed Ranking	Verbal interpretation
Sodium Chloride	2	Sodium Chloride had the second Most bubbling amongst the three electrolytes
Sodium Bicarbonate	3	Sodium Bicarbonate had the Least bubbling amongst the three electrolytes
Sodium Hydroxide	1	Sodium Hydroxide had the Most bubbling amongst the three electrolytes

Table 2, titled "Observed oxyhydrogen production speed of each electrolyte at optimal conductivity," ranks the three different electrolytes, sodium chloride, sodium bicarbonate, and sodium hydroxide, based on their observed bubbling. Based on the table, Sodium hydroxide ranks first amongst the three electrolytes, meaning that it had the most observed bubbling amongst the three electrolytes. On the other hand, Sodium Bicarbonate ranked last, meaning it had the least observed bubbling amongst the three electrolytes. Sodium chloride ranked second

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amongst the three, meaning it had less bubbling than sodium hydroxide but more bubbling than sodium bicarbonate.

The table shows the ranking in oxyhydrogen production speed of each electrolyte, with sodium hydroxide having the most bubbling amongst the three, and sodium bicarbonate having the least bubbling. However, there are other factors to be taken into consideration, such as side reactions other than oxyhydrogen production. Such side reactions were present in sodium chloride, which produced chlorine gas, hindering the purity of the oxyhydrogen gas. Based on the previous researchers by Yusof et al and Rusdianasari et al, sodium hydroxide is known to be the most conductive amongst the three electrolytes, is very abundant, and produces the purest oxyhydrogen gas without undergoing side reactions, which aligns with this research's findings.

Table 3. Observable effects measured on a Likert scale

Electrolyte	Effect	Effect Trend	P-Value	Verbal interpretation
Sodium Chloride	Foaming	Increase	0.0010	Foaming, deterioration, and turbidity increase throughout the experiment
	Deterioration	Increase	0.0027	
	Turbidity	Increase	0.0006	
Sodium Bicarbonate	Foaming	No Trend	1.0000	Foaming and deterioration do not change during the experiment, but turbidity increases
	Deterioration	No Trend	0.1637	
	Turbidity	Increase	0.0142	
Sodium Hydroxide	Foaming	No Trend	0.2963	Deterioration and turbidity increase during the experiment, but foaming does not
	Deterioration	Increase	0.0050	
	Turbidity	Increase	0.0022	

Note: Not Significant Trend ≥ P-Value 0.5 > Significant Trend

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Table 3, titled "Observable effects measured on a Likert scale," shows the effects that the researchers observed and measured on a Likert scale during the 45 minutes of electrolysis, including foaming, deterioration, and turbidity. The table also shows the trend of each of these effects throughout the experiment using the p-value, which helps indicate if the trend is statistically significant or not. A lower p-value indicates stronger evidence that a monotonic trend is statistically significant, whereas a higher p-value indicates weaker evidence and is consistent with no significant trend. All of the electrolytes have 3 effects each: foaming, deterioration, and turbidity. In Sodium Chloride, the most statistically significant trend is turbidity with a 0.0006 p-value, and the least significant trend, which is deterioration, with a p-value of 0.0027. The foaming trend showed a statistically significant moderate increase compared to the other two trends, with a p-value of 0.0010. In Sodium Bicarbonate, the highest statistically significant trend with a p-value of 0.0142 is Turbidity, while foaming and deterioration showed no statistically significant trends; foaming still had the highest p-value of 1.0000. Deterioration was set in the middle level of the two, with a p-value of 0.1637. In Sodium Hydroxide, Turbidity had the most statistically significant trends with a p-value of 0.0022, while foaming had no statistically significant trend, but the lowest p-value of 0.2963. The deterioration trend showed a statistically moderate increase, which placed it in the middle of both trends, with a statistically significant increasing trend and a p-value of 0.0050. In comparison, the electrolyte with the highest statistically significant increase in foaming, deterioration, and turbidity is Sodium Chloride, with the p-values of 0.0010, 0.0027, and 0.0006, respectively. This indicates that the production of foam, deterioration of graphite, and turbidity were at their highest increase in Sodium Chloride.

The table shows the different observable effects of the 3 electrolytes used. It is prominent that the most increasing of the observable effects amongst the electrolytes used was Sodium Chlorine, with foaming having a p-value of 0.0010, deterioration having a p-value of 0.0027, and turbidity with a p-value of 0.0006, all showing a statistically significant increase in trend. According to a research, "The Effect of Salt on Stability of Aqueous Foams", which showed that adding 18% NaCl made the water density increase by 15%, which lowers the formation of foam but because of high water density, there is also high ionic strength which lowers surface tension that helps in increasing of formation of foam (Obisesan., et al., 2020). As for Sodium Bicarbonate, there was no trend, as water does not react with baking soda, which means no buildup of foam (Science Buddies, 2015). As for Sodium Hydroxide, the foaming occurred only due to steam released from the hydrated sodium and calcium silicate (da Silva, R., et al., 2019). Furthermore, according to the research, "Deterioration of Telecommunication Equipment and Facilities in Salt-damage Environments—Case Studies of Corrosion in Guy Wires and Maintenance Holes", the residual strength of the wires had decreased by an average of 77% which proves that sodium chloride has a high increase in deterioration of wires amongst the 3 electrolytes used, meaning that the wires strength was weakened the most by sodium chloride (NTT, 2023). As for Sodium Bicarbonate, the copper wires had a strong resistance against the solution, causing it to not have an increase in deterioration, thus staying the same (Daud et al, 2006). As for Sodium Hydroxide, copper wires slowly corrode due to the pH level increase, as the solution gets more alkaline, the effect of corrosion decreases (Sugiura et al, 2024). Additionally, a research, "A Study: Salinity and Turbidity", talked about how the higher the salinity, the higher the turbidity and vice versa. Amongst the 3 electrolytes that were used, sodium chloride had the highest salinity amongst all, which means that it would have the highest turbidity amongst all as well (Yee, 2020). As for Sodium Bicarbonate, mixing it with drinking water increases salinity, thus increasing turbidity (Martinez, Y., et al., 2021). As for Sodium Hydroxide, dosed NaOH can have a high concentration, which leads to an increase in turbidity (Kesler, V., et al., 2013).

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Table 4. Observable effects of the electrolytes on the cathode and anode wires

Electrolyte	Discolored Wire	Color Observed	Time Observed	Verbal interpretation
Sodium Chloride	Anode	Silver	10, 15, 20, 25, 30, 35, 40, 45 Minute Marks	The anode turned a silver color at the 10, 15, 20, 25, 30, 35, 40, and 45 minute marks. The cathode turned black at the 40 and 45 minute marks. Both the cathode and the anode changed color to patina after the experiment.
	Cathode	black	40 and 45 Minute Marks	
	Cathode & Anode	Patina	After Experiment	
Sodium Bicarbonate	Anode	Silver	5, and 35 Minute Marks	The anode turned a silver color at the 5, 35, 40, and 45 minute marks. The cathode turned black at the 5-minute mark. Both cathode and anode turned to a silver color at the 40 and 45 minute marks. Both the anode and the cathode change to black after the experiment.
	Cathode	Black	5 Minute Mark	
	Cathode & Anode	Silver	40, and 45 Minute Marks	
	Cathode & Anode	Black	After Experiment	
Sodium Hydroxide	Anode	Black	5 Minute Mark	The anode changes to a black color at the 5-minute mark, and the cathode also turns the same color at the 15, 20, 25, 30, 35, 40, and 45-minute marks, and after the experiment.
	Cathode	Black	15, 20, 25, 30, 35, 40, 45 Minute Marks & After Experiment	

Table 4 introduces the observable effects of the electrolytes on the cathode and anode wires. For sodium chloride, the anode turned into a silver color at the 10, 15, 20, 25, 30, 35, 40, 45 minute marks and turned into a patina color at the end of the experiment. The cathode exhibits a change in color to black at the 40 and 45 minute mark, and to a patina color at the end of the experiment. Sodium bicarbonate shows the same behaviour at the anode by turning a silver color at a time of 5 and 35 minute marks. The cathode shows a change in color to black at only the 5-minute mark. However, both cathode and anode turned to a silver color at the 40 and 45 minute mark and turned black at the end of the experiment. For sodium hydroxide, the anode turned black only at the 5-minute

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mark. However, the cathode turned a black color at the 15, 20, 25, 30, 35, 40, and 45 minute marks, and after the experiment was done.

The color changes observed in the anode and cathode of the wires of each solution can be explained by chemistry. For sodium chloride, the copper wire changes color to black or patina due to the copper oxidation after it interacts with oxygen in the electrolysis cell (McKeachie, 2022). The patina color observed on the wires and in the water also indicates the production of chlorine gas. Additionally, sodium chloride and sodium bicarbonate exhibit such colors during the experiment observations due to copper oxidation. The black is also most prominently present in electrolysis of low voltages (< 5V) according to a study by Brudzisz et al, about Low-voltage anodizing of copper in sodium bicarbonate solutions in 2023. Additionally, the observed silver color in the cathode and anode of sodium chloride and bicarbonate can be attributed to copper oxides giving off a metallic luster under certain conditions; however, this has limited documentation, yet it aligns with the electrochemical behaviour of copper in such environments. As for sodium hydroxide, the colors observed on its cathode and anode can also be explained by copper oxidation due to the wire interacting with oxygen. The voltage in the experiment was kept at a low voltage of 4, as the wires were too thin to handle any higher voltages according to the power supply, which would overload and halt the current when 4 volts were exceeded.

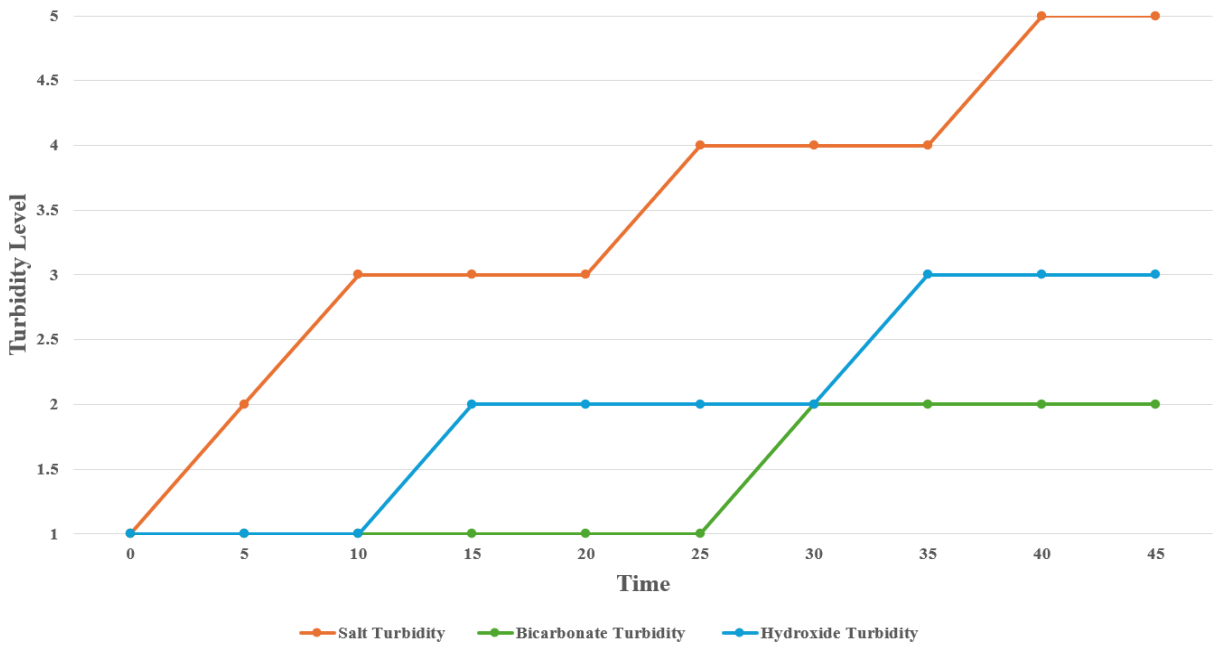

Figure 2. Foaming Trend Graph

Figure 2, titled “Foaming Trend Graph”, shows the foaming trends observed during the electrolysis experiment. The graph shows the foaming trends for sodium chloride as the color blue, sodium bicarbonate as the color

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orange, and sodium hydroxide as the color green. For sodium chloride, the graph shows a steady increase in foaming from no foam to moderate foam during the first 10 minutes, with 0.333 points per 5-minute interval. Later on, from the 10-minute mark to the 20-minute mark, the foaming continues to be at moderate foaming before increasing to excessive foam from the 20-minute mark to the 25-minute mark. This increase is then stopped from the 25-minute mark to the 40-minute mark. Lastly, the foaming increased from excessive foam to extreme foam from the 40-minute mark to the 45-minute mark. Sodium bicarbonate shows no foaming trend as it remains in no foam throughout the whole experiment. Sodium hydroxide exhibits a similar behaviour, except there is a spike in foaming at the 5-minute mark, to mild foam, but then goes back to no foam for the rest of the experiment.

During electrolysis in a sodium chloride solution, foam production increased steadily from “no foam” to “moderate foam” over the first ten minutes, remained at moderate levels until 20 minutes, then jumped to “excessive foam” by 25 minutes and plateaued there until 40 minutes before rising to an “extreme foam” level by the end of the 45 minute run, this behaviour reflects both rapid H_2/O_2 bubble nucleation and the surfactant-like stabilizing effect of chloride ions on bubble films (Bard & Faulkner, 2001; Trasatti & Petrii, 1992). In contrast, the sodium bicarbonate electrolyte produced virtually no foam throughout the entire experiment, a result of lower ionic strength and the generation of CO_2 bubbles, which detach more readily and fail to coalesce at the surface (Yang & Chung, 2008). Sodium hydroxide, despite its high conductivity and immediate gas evolution, exhibited only a brief spike to mild foam at around five minutes; because hydroxide (OH^-) ions do not stabilize bubble films as effectively as chlorine (Cl^-), the foam collapsed quickly and the solution returned to “no foam” for the remainder of the experiment (Bard & Faulkner, 2001).

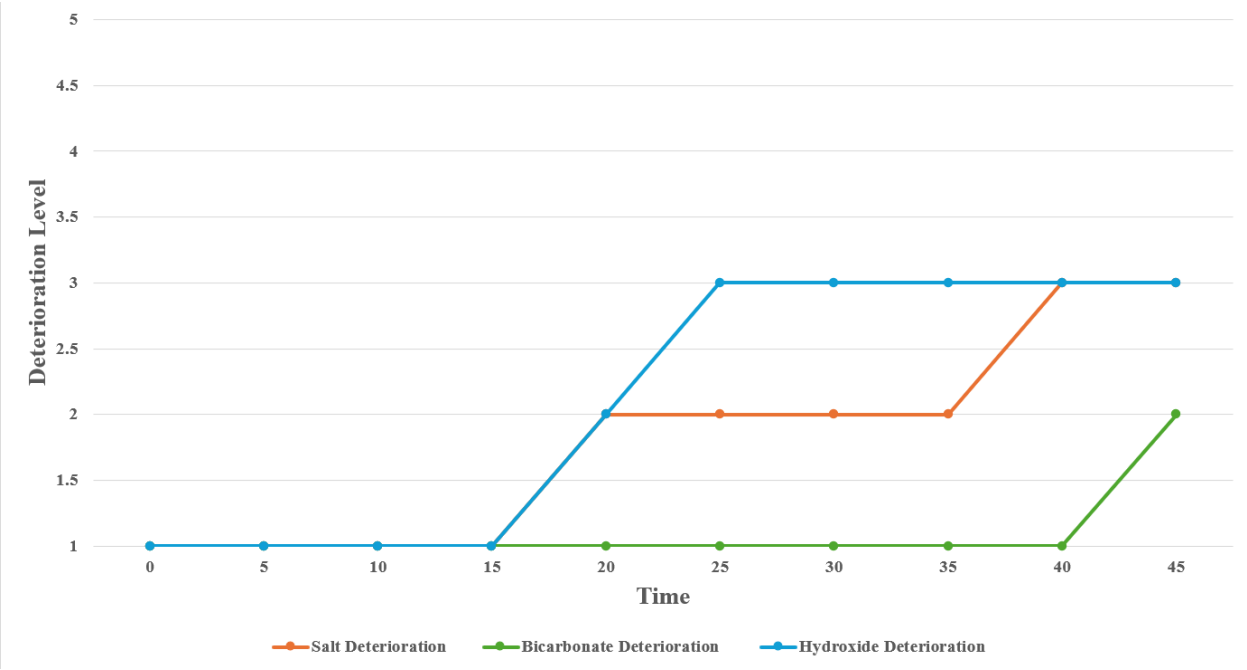

Figure 3. Deterioration Trend Graph

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Figure 3, titled "Deterioration Trend Graph", shows the deterioration trends observed during the electrolysis experiment. The graph shows the deterioration trends for sodium chloride as the color blue, sodium bicarbonate as the color orange, and sodium hydroxide as the color green. Sodium hydroxide shows no graphite deterioration from the 0-minute mark to the 15-minute mark. Then the deterioration spikes to moderate deterioration, which shows a change in color of the graphite, at the 25-minute mark, with a rate of change of 0.286 pointer per 5-minute interval. Later on, the deterioration does not change throughout the experiment. Sodium chloride exhibits the same behaviour, with a rate of change of 0.250 pointer per 5-minute interval, but the spike is to a minor deterioration at the 15-minute mark. Deterioration then remains at that level from the 15-minute mark to the 35-minute mark, where it goes up again to moderate deterioration, this time till the end of the experiment. Sodium bicarbonates remain at no deterioration from the 0-minute mark to the 40-minute mark, then deterioration rises to minor deterioration by the end of the experiment.

During electrolysis, in the sodium hydroxide solution, the graphite electrode showed no visible deterioration from 0 to 15 minutes, but by the 25-minute mark, it exhibited moderate surface deterioration, which lasted till the end of the experiment. This behaviour is consistent with hydroxide ions, which induce carbon oxidation and surface etching under strongly alkaline conditions (Bard & Faulkner, 2001). In contrast, sodium chloride produced a minor deterioration spike at the 15-minute mark, likely due to chlorine ions mediated pitting corrosion, and held steady at that level until the 35-minute mark, after which deterioration rose to a moderate level by the 45-minute mark as chloride ions progressively attacked grain boundaries in the graphite structure (Trasatti & Petrii, 1992). The sodium bicarbonate electrolyte remained essentially protective, showing no discernible graphite oxidation until the final five minutes, when a slight, minor deterioration appeared, a reflection of the relatively low corrosivity of bicarbonate ions and the slow kinetics of carbonate-facilitated carbon corrosion at the applied potentials (Bard & Faulkner, 2001).

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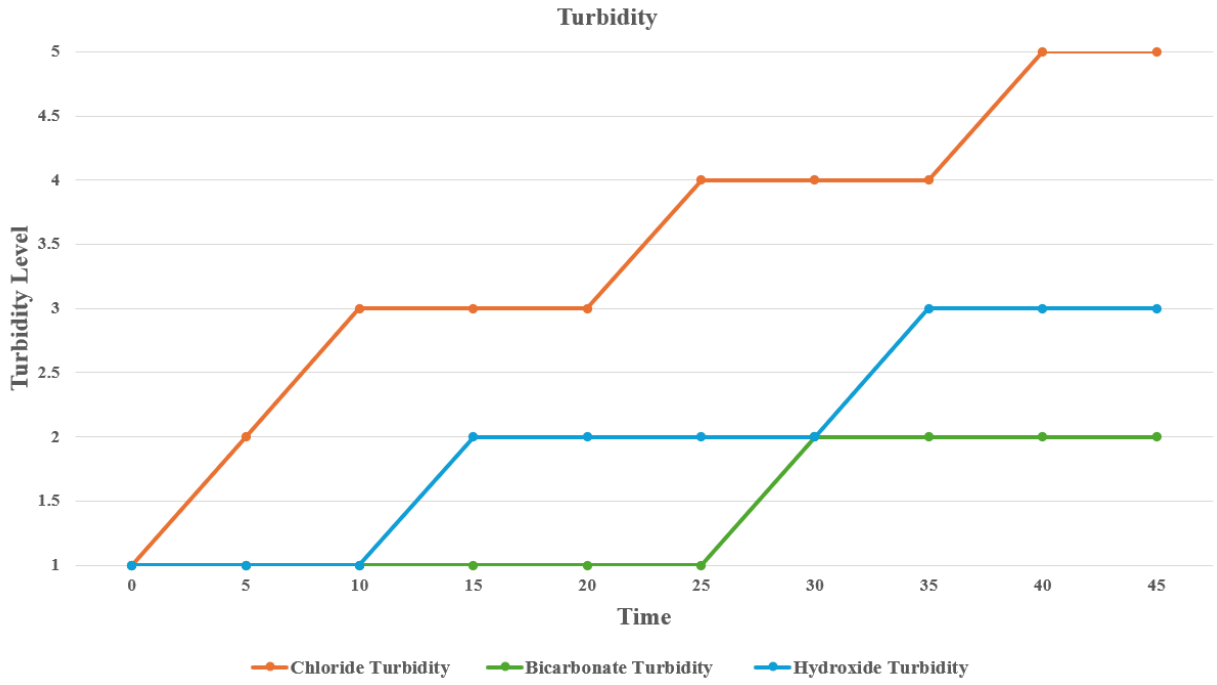

Figure 4. Turbidity Trend Graph

Figure 4, titled "Turbidity Trend Graph", shows the Turbidity trends observed during the electrolysis experiment. The graph shows the Turbidity trends for sodium chloride as the color blue, sodium bicarbonate as the color orange, and sodium hydroxide as the color green. Sodium chloride exhibits a steady increase from the 0-minute mark to the 10-minute mark, from very clear to moderately turbid, with a rate of change of 0.4 points per 5-minute interval, then the turbidity remains the same from the 10-minute mark to the 20-minute mark. The turbidity rises again from the 20-minute mark to the 25-minute mark, water becomes very turbid. The water then remains at the same level from the 25-minute mark to the 35-minute mark before it rises again to extremely turbid till the end of the experiment. Sodium hydroxide's water remains at very clear from the 0-minute mark to the 10-minute mark, after that, it rises to slightly turbid from the 10-minute mark to the 15-minute mark, with a rate of change of 0.25 per 5-minute interval, and then remains at that level until it rises again to moderately turbid from the 30-minute mark to the 35-minute mark, and then remains at that level to the end of the experiment. Sodium Bicarbonate rises to slightly turbid from the 25-minute mark to the 30-minute mark, with a rate of change of 0.125 per 5-minute interval, and remains at that level for the rest of the experiment.

During electrolysis in the sodium chloride solution, the water transitioned from very clear to moderately turbid within the first ten minutes, the water held at that level until about the 20-minute mark, then jumped to very turbid by the 25-minute mark and remained there until a final rise to extremely turbid by the 40-minute mark. This behaviour is attributable to rapid chloride-mediated graphite and electrode particulate release combined with vigorous gas–particle interactions that scatter light (Bard & Faulkner, 2001; Comninellis & Pletcher, 2011). In the

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sodium bicarbonate solution, turbidity stayed at a very clear level until around the 30-minute mark, when it climbed to a slight turbidity and then stabilized for the remainder of the experiment. This behaviour is consistent with the slower kinetics of carbonate-driven electrode corrosion and the delayed formation of fine suspended particles (Trasatti & Petrii, 1992). Sodium hydroxide exhibited a small turbidity increase from clear to slightly turbid between 10 and 15 minutes, plateaued until about the 30-minute mark, and then rose to moderate turbidity through the rest of the experiment, reflecting early hydroxide ions induce graphite etching that releases colloidal carbon fragments, followed by a steady state as surface etching rates declined (Bard & Faulkner, 2001).

5. Implications of the Study

The data presents the optimal electrolyte concentration that maximizes conductivity, and the electrolyte with the highest conductivity is sodium hydroxide. This may entail that sodium hydroxide could be the optimal electrolyte amongst the three electrolytes for oxyhydrogen production. Sodium hydroxide had the most amount of bubbles produced during the experiment, which indicates that sodium hydroxide is the fastest in oxyhydrogen production amongst the three electrolytes. The electrolyte with the most foaming was sodium chloride, and the color silver was observed on its anode wire, black on its cathode wire, and patina on both its cathode and anode. The electrolyte with the most deterioration is sodium hydroxide, and the color black was observed on its anode and cathode wires. The electrolyte with the most turbidity was sodium chloride. The electrolyte with the least foaming was sodium bicarbonate, and the colors silver and black were observed on its anode and cathode wires, respectively. The electrolyte with the least deterioration was sodium bicarbonate. Lastly, the electrolyte with the least turbidity was sodium bicarbonate. This data implies that sodium bicarbonate had the least amount of negative effects, which were foaming and deterioration, and sodium chloride had the most negative effects, which were foaming, deterioration, and the production of chlorine gas. Sodium hydroxide had the second least negative effects, but worse than sodium bicarbonate. Within the trend of foaming, the electrolyte with the highest rate of change was sodium chloride. Within the trend of deterioration, the electrolyte with the highest rate of change was sodium hydroxide. Finally, within the trend of turbidity, the electrolyte with the highest rate of change was sodium chloride. This data entails that, in terms of change, sodium bicarbonate had the least amount of negative changes throughout the experiment, while sodium chloride had the most amount of increase in terms of negative changes during the period of the experiment. Additionally, the data implies that sodium hydroxide had the second least increase in the negative changes throughout the experiment.

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6. Conclusion and Recommendations

Conclusion

Based on the analyzed and contextualized data, both null hypotheses were rejected. Due to there being a significant increase in trends observed during electrolysis, there was a significant rate of change for each effect throughout the experiment. Furthermore, based on the analyzed data, sodium hydroxide—amongst the three electrolytes—is the optimal electrolyte to be used in electrolysis for oxyhydrogen production.

Recommendations

As synthesized from the findings and conclusions of this study, Hydrologists are recommended to use sodium hydroxide at 5 grams per 100 millilitres of water. The use of sodium hydroxide provides the most oxyhydrogen with the best purity. Automotive Engineers are recommended to use thicker and more durable wires to increase the system's longevity and improve production. The researchers applied sodium hydroxide at the optimal concentration and showed efficiency and minimal increase in the deterioration of wires compared to sodium chloride. Refrain from using sodium chloride as it corrodes copper wires. Environmentalists are recommended to be aware of the harmful side effects of using sodium chloride as an electrolyte, as it produces chlorine gas, which is very harmful to the environment. Car manufacturers are recommended to use sodium hydroxide, at a concentration of 5 grams per 100 millilitres, as this is the most conductive electrolyte, thus producing the most oxyhydrogen at the optimal purity. Hydrogen Fuel Consumers are recommended to understand the process of making hydrogen fuel, including which electrolyte to use and at what concentration. Additionally, the researchers suggest avoiding the use of sodium chloride's hydrogen as it produces the least pure gas with the most harmful side effects. Future researchers are recommended to understand the limitations of this study and further improve on the apparatus used.

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