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A Comparison of Photocatalysis and Electrocoagulation for Azo Dye Treatment and a Novel Use of H_2 PEM Fuel Cells for Simultaneous Renewable Energy Generation

Original Article

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Abstract: Textile dyes are a major contaminant in water, but many removal methods require large amounts of energy. Our study's purpose was to optimize two removal processes- photocatalysis and electrocoagulation- and measure the amount of energy that could be generated during electrocoagulation using the byproduct hydrogen gas. pH, catalyst concentration, and dye concentration were tested for photocatalysis; voltage, pH, and dye concentration were tested for electrocoagulation, and a novel method with 3D printed-lids and hydrogen fuel cells was used to generate energy. Photocatalysis was successful across almost all parameters, and the optimized process - pH 9, 0.1 g/L TiO_2, and 50 mg/L of methyl orange- broke down 97.8% of all dye. Electrocoagulation broke down over 98% of dye at 5V, pH 7, and 50 mg/L methyl orange. The novel energy recapture process recovered up to 20% of the energy put into electrocoagulation, doubling the hypothesis, meaning it could be used in the future to make electrocoagulation 20% more efficient. Electrocoagulation was 6.44 times more energy efficient than photocatalysis and 35%-46% more cost-effective than traditional methods.

Keywords: Photocatalysis • Azo Dyes • Methyl Orange • Titanium Dioxide (TiO_2) • Electrocoagulation• Hydrogen• Renewable Energy • PEM Fuel Cell

1. Introduction

According to Hossain et al., in 2018, textile industries produce a significant amount of the world's wastewater, especially in developing nations [1]. This dye-contaminated textile wastewater can contain strong color, suspended particles, and non-biodegradable materials, which are often toxic or carcinogenic [2]. Wastewater purification often also requires electricity, and about 80% of the world's energy comes from fossil fuels, which cause air pollution as well as global warming [3]. Two potential methods for remediating dyes are photocatalysis and electrocoagulation.

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Electrocoagulation can also be used to generate hydrogen [4], which can provide a clean source of electricity, reducing the energy burden of dye purification processes. One water purification process is photocatalysis - the use of light to activate a catalyst, which in turn participates in the acceleration of a chemical reaction. In the process of photocatalysis, light hits the catalyst (normally TiO_2 or ZnO), and an electron is excited. This electron (e^-_{cb}) “jumps” from the valence band to the conduction band of the catalyst, leaving behind a hole (h^+_{vb}) in the valence band [4]. The electrons and holes are critical for the overall process, as they then react with water and oxygen. In this step, both hydroxyl radicals (OH^-) and superoxide ions O_2^{2-} are produced [5]. These compounds are not very stable, but are very good at degrading organic pollutants, such as textile dyes. In this process, organic pollutants are oxidized and then mineralized, breaking down into carbon dioxide and harmless, inorganic ions [5].

Another method of purifying water is electrocoagulation. Electrocoagulation is the process by which an electric current is run through two electrodes (anode and cathode) submersed in water. The electrodes are separated, which causes contaminants between the electrodes to become polarized and reactions to occur at the electrodes themselves. At the cathode, hydrogen gas and OH^- radicals are produced through electrolysis [2]. The more chemically reactive the metal is (the less stable its electron configuration is), the more H_2/OH^- it will generate [6]. At the anode, metal ions are released. These ions combine with the OH^- generated at the cathode to form metal hydroxides. The hydroxides attach via charge differential to any polarized particle in the water, clumping contaminants together into flocs (complexes of contaminants and metal hydroxides) large enough to settle or be filtered. The most common metals used in electrocoagulation are aluminum and iron [2].

Hydrogen gas, which can be captured as a byproduct of electrocoagulation, is becoming a promising future source of energy [7]. Hydrogen is most commonly produced using electrolysis (such as electrocoagulation), a method of splitting H_2O into H_2 and $\frac{1}{2}O_2$ using electricity [6]. While hydrogen can be generated in other ways, water is by far the most abundant source as well as a very efficient source of hydrogen. One of the most efficient ways of using the hydrogen as a fuel is running it through a proton exchange membrane fuel cell (PEMFC). To generate electricity, H_2 is fed on one side of the proton exchange membrane while O_2 (air) is fed on the other. When an electrical load is applied, H_2 splits into H^+ ions. The H^+ ions cross the membrane while the electrons are left behind. The electrons are used to create an electric circuit, and then combine with H^+ and O_2 to form H_2O. The amount of current produced by the fuel cell is proportional to the flow rate of hydrogen and oxygen [8].

In 2019, Çokay and Gürler found that increasing the voltage being put into electrocoagulation led to an increase in H_2 production [3]. Chen et al. in 2017 studied the effects of initial pH, dye concentration, and photocatalyst (zinc oxide) concentration for dye degradation. It was found that acidic pH’s, low dye concentrations, and high doses of ZnO led to the highest degradation rates [9].

1.1. Purpose, Hypothesis, and Engineering Goals

Purpose

The purpose of this study was to compare and optimize photocatalysis and electrocoagulation in the remediation of methyl orange dye and to determine how the following variables affected those two processes:

- pH, TiO_2 concentration, and dye concentration for photocatalysis
- voltage, pH, and dye concentration for electrocoagulation
- A novel method was employed aiming to determine how much renewable energy could be produced (recaptured) via H_2 gas collected from electrocoagulation, which would address two environmental problems (contaminated water and over-reliance on fossil fuels) at once.

Alternate Hypothesis

An acidic pH, higher catalyst concentration, and lower dye concentration will lead to the most efficient photocatalytic system. Electrocoagulation efficiency will increase with an increase in voltage, a decrease in initial dye concentration, and a high pH. About 11% of the energy being put into electrocoagulation can be recovered through hydrogen fuel cells.

Null Hypothesis

pH, dye concentration, and titanium dioxide concentration will have no effect on the photocatalytic degradation system. Voltage, dye concentration, and pH will have no effect on the efficiency of electrocoagulation. Percent energy recapture from electrocoagulation using hydrogen gas will be negligible.

Engineering Goals

Lids will be designed and 3D printed to hold the electrodes for electrocoagulation and capture hydrogen. A novel system to generate and measure energy will be constructed.

2. Methods

2.1. Making and Measuring Methyl Orange Solutions

Methyl orange solutions were made by adding 0.05% methyl orange by mass aqueous solution (Carolina Biological) to distilled water. Methyl orange was transferred via a small graduated cylinder into a 150 mL beaker to make either a 50 or 100 mL solution, having concentrations of 50, 100, or 150 mg/L.

2.2. Measuring Dye Concentration

The optimal wavelength to measure the methyl orange concentration was determined by measuring the absorbance spectrum of methyl orange in a spectrophotometer (Vernier Go-Direct UV Vis Spectrophotometer). The peak wavelength was the wavelength at which all absorbance values were measured during trials. A Beer's

Law Plot of methyl orange was created using dye concentrations between 0 and 200 mg/L. A linear regression (line of best fit) was run between dye concentration and absorbance, which was then used for all trials to determine the final dye concentration and removal efficiency. The R-squared value was calculated for the regression to determine the strength of the correlation between absorbance and concentration.

2.3. Photocatalysis

2.3.1. General Process/Procedure

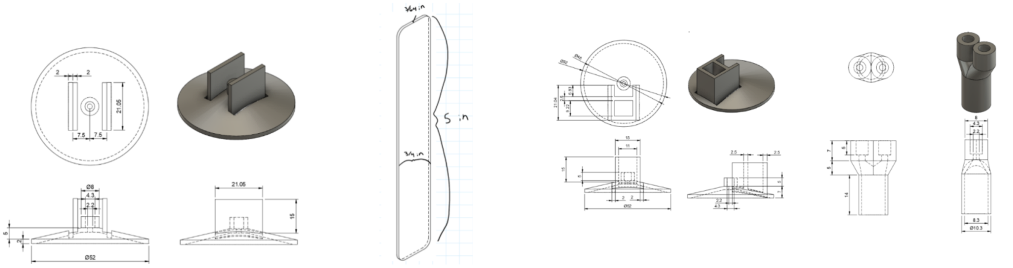
First, 50 mL aqueous solutions of 50, 100, or 150 mg/L methyl orange dye were made in 100mL beakers [4]. Then, if needed, pH was altered through the application of 0.1 molar HCl or NaOH, which were purchased from Carolina Biological. The amount of titanium dioxide needed for each trial (with concentrations ranging from 0.1 to 1 gram per liter of solution) was measured and then stirred into the 50 mL solution to initiate the process. The titanium dioxide was purchased as a mixture of rutile and anatase from Sigma Aldrich. The solutions were kept in a cabinet under a UV radiation lamp (UV-B) to ensure that the light from the UV lamp was the only light they received. In accordance with Chen et al., in 2017, an 8.5 cm distance was kept between the UV light source and the solution [9], resulting in an average light intensity of 1.8 W/m^2. Samples for each trial were taken from solutions after 24 hours, and the solutions were centrifuged at 12,000 rpm for 10 minutes to create a pellet of TiO_2 that could be filtered out. The absorbance at the peak wavelength was measured using a Vernier GoDirect UV-Vis Spectrophotometer [4]. Absorbance in a spectrophotometer was compared to the initial absorbance of that concentration of dye to assess what percentage of the orignal dye had been degraded (% left = (A_{final} / $A_{initial}$)*100). This works because the Beer's Law plot is linear, so the ratio of the absorbances equals the ratio of the concentrations.

First, pH was tested, at 3, 5, 7, 9, and 11. To alter the pH of the solution, 0.1 molar HCl or NaOH were added with the required volumes to the 50 mL solution of distilled water prior to the addition of the titanium dioxide. To make sure that the pH was accurate, the Vernier pH probe was used before starting trials. Dye concentration was set to 50 mg/L, and TiO_2 concentration to 0.1 g/L. Then, using the optimal pH for dye removal, the concentration of the photocatalyst (TiO_2) was altered, with concentrations of 0.1 g/L, 0.5 g/L, and 1 g/L being used in solutions with 50 mg/L of dye. Finally, with the optimal pH and TiO_2 concentration, methyl orange concentration was altered to 50 mg/L, 100 mg/L, and 150 mg/L [4]. Dye concentration was a manipulated variable in order to see if high degradation rates could be maintained when there was more dye to break down, and because it has been frequently tested in previous studies [4, 9]. This system of testing variables sequentially and using the best-functioning operational parameters for the next step allowed us to optimize the process.

2.4. Electrocoagulation

2.4.1. Beaker/Lid Setup

The electrocoagulation system used a pair of iron electrodes in a 150 mL beaker (5.7 cm x 8.6 cm) with a PLA 3D printed lid. Electrocoagulation had two phases: dye removal and energy generation. For dye removal trials, the lids contained two slits to hold the two electrodes (Figure 1a). The electrodes were secured to the lid using rubber bands. For energy production trials, a different lid (Figure 1b) was designed and 3D printed to hold the electrodes and capture hydrogen. There was a hole in the middle for hydrogen to flow through a 3D printed adaptor that allowed two silicone tubes to be attached to the lid and transport the hydrogen gas to two hydrogen fuel cells.



(a) Schematic of Electrocoagulation Lid for Dye Removal (mm), and Electrode (in.)

(b) Schematic of Electrocoagulation Lid and Adapter (mm) Used for Energy Production Trials

Figure 1. **3D printed parts used in electrocoagulation (a) and hydrogen capture trials (b)**

2.4.2. Dye Removal

Supplying Power

A DC power supply (Carolina Biological) was used to supply 2.5V or 5V at 40 A/m^2 to the electrodes using alligator clips.

Procedure

The effects of voltage, pH, and dye concentration were tested, with each variable being utilized for the total length of the trial. The effects of voltage were tested first at 2.5 and 5 volts. The voltage was set using the power supply. The concentration of methyl orange was 50 mg/L and the pH was 7. Next, trials testing pH at 3, 5, 7, 9, and 11 were run with 50 mg/L methyl orange and the optimal voltage for electrocoagulation. Lastly, the effects of dye concentration at 50, 100, and 150 mg/L were measured using the optimal voltage and pH for dye removal.

Each trial was run for 20 minutes and then filtered using Whatman filter paper. After electrocoagulation, the amount of methyl orange remaining was calculated by measuring the solution's absorbance at the optimal wavelength in a spectrophotometer. Percent removal was calculated with the equation (Absorbance$_{final}$/Absorbance$_{initial}$)*100. The absorbance of the solution was compared against the Beer's Law plot to obtain the concentration of methyl orange. A cost analysis was also run, comparing the cost of the study's electrocoagulation setup to that of traditional wastewater treatment methods.

2.4.3. Energy Production Using Hydrogen Fuel Cells

This phase was conducted to test how much electrical power could be generated from the H_2 gas produced during electrocoagulation. Each trial was run using 100 mL of distilled water with 3.5g of NaCl. The salt concentration was chosen because it is the average concentration of salts in seawater: 35 g/L [10]. The electrocoagulation took place with the second lid design and the adapter (Figure 2). The lid used silicone tubes to direct generated hydrogen gas to two fuel cells (Horizon PEM Mini Fuel Cell). The fuel cells were connected in series to produce twice the output voltage of one fuel cell. The output of the fuel cells was connected to a Horizon Energy Monitor to measure the amount of voltage, amperage, and wattage produced. A motor was used as the electric load to draw current. After the voltage from the hydrogen fuel cell increased to its maximum, the motor was connected to the fuel cell monitor, and the output power was measured in watts. This was then divided by the input power (W) from the power supply to find the percent recaptured energy ($100 * W_{output} / W_{input}$). This method was novel, because while some studies have tested how much hydrogen could be produced from electrocoagulation, no other study has attempted to measure the energy that could be generated from this hydrogen.

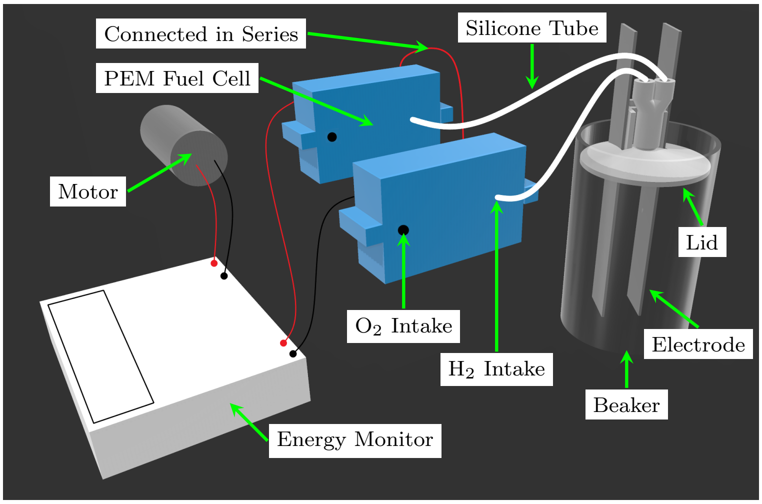


Figure 2. **Labeled Diagram of the Novel Hydrogen Capture / Energy Generation Setup**

3. Results

3.1. Absorbance Spectrum

Methyl orange reached a maximum absorbance at 466 nm, so this became the wavelength the absorbance was measured at for all other trials in order to achieve maximum accuracy in the results and provide a baseline standard of comparison (Figure 3).

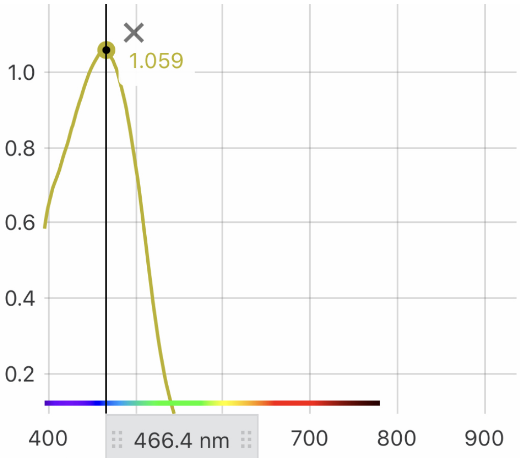


Figure 3. **The Absorbance Spectrum of Methyl Orange (Absorbance as a Function of Wavelength)**

3.2. Beer's Law Plot

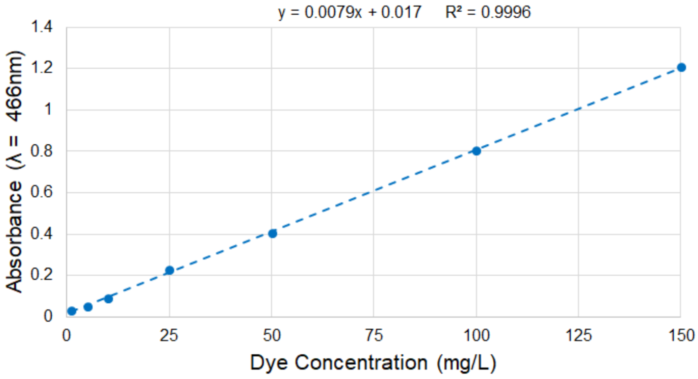


Figure 4. **Absorbance of Methyl Orange as a Function of its Concentration (mg/L) (Beer's Law Plot)**

Figure 4 shows that the correlation between the concentration of methyl orange and absorbance was very strong, with an R^2 value of 0.999, indicating 99.9% of the variation in absorbance can be explained by the least squares regression of absorbance on concentration. The line of best fit (produced from a linear regression) was $A = 7.96 * 10^{-3}C + .0134$, where A = absorbance and C = concentration of methyl orange (mg/L). This was used to determine how much methyl orange (in mg/L) was left in each solution after each trial using the absorbance recorded.

3.3. Dye Removal Trials

Effect of pH

Figure 5 displays that both photocatalysis and electrocoagulation were successful and resulted in the removal of the vast majority of dye across all pH values, with the exception of pH 11 for photocatalysis. Roughly 70%

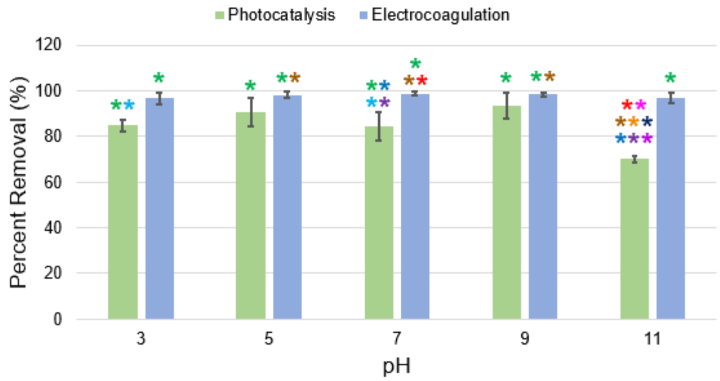
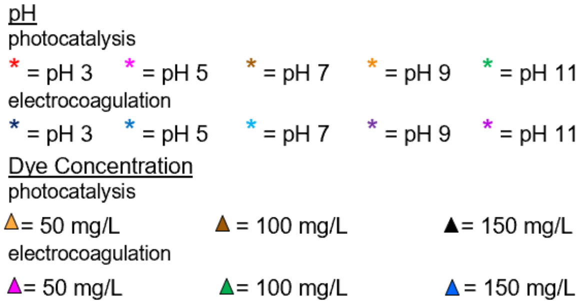


Figure 5. Effect of pH on Percent Removal in Photocatalysis and Electrocoagulation (n=3)



pH
photocatalysis
* = pH 3 * = pH 5 * = pH 7 * = pH 9 * = pH 11
electrocoagulation
* = pH 3 * = pH 5 * = pH 7 * = pH 9 * = pH 11
Dye Concentration
photocatalysis
▲= 50 mg/L ▲ = 100 mg/L ▲= 150 mg/L
electrocoagulation
▲= 50 mg/L ▲= 100 mg/L ▲= 150 mg/L

Figure 6. Key Denoting Significance in Dye Removal Trials (To be Used in Conjunction with Figures 5 and 7). I.E - red star indicates that the group was significant to photocatalysis pH 3.

of the dye was removed in this group, while all other groups had dye removal rates well above 80%. In certain groups, such as pH 7 for electrocoagulation, the dye removal rate was nearly 100%. Stars are used to indicate significance (Figure 6), as determined by a one-way ANOVA followed by a Post-Hoc Scheffe ($p < 0.05$).

Effect of Dye Concentration

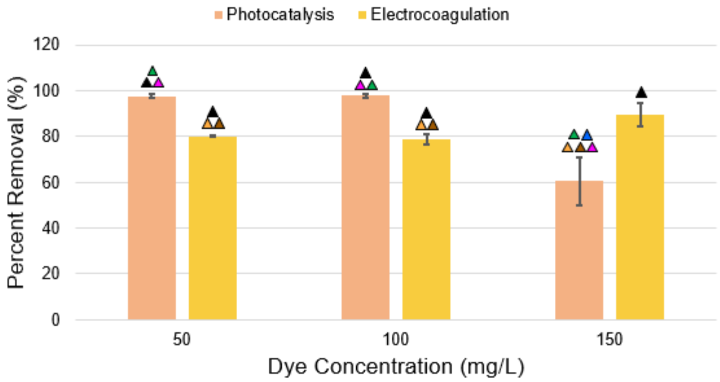


Figure 7. **Percent Removal of Dye as a Result of Initial Dye Concentration in Photocatalysis and Electrocoagulation (n= 3)**

Figure 7 shows that the 50 and 100 mg/L groups for photocatalysis resulted in near 100% removal of dye, but removal was significantly lower for the 150 mg/L group, with only about 60% of dye being broken down. For electrocoagulation, the percentage of dye removed was fairly consistent across groups, as about 80% of the dye was coagulated no matter what the initial concentration. The fact that most of the dye can be removed across the entire range of parameters indicates the usefulness of these two methods. Triangles are used for significance, to be compared with the key (Figure 6), again determined by a one-way ANOVA followed by a Post-Hoc Scheffe ($p < 0.05$).

Effect of TiO_2 Concentration

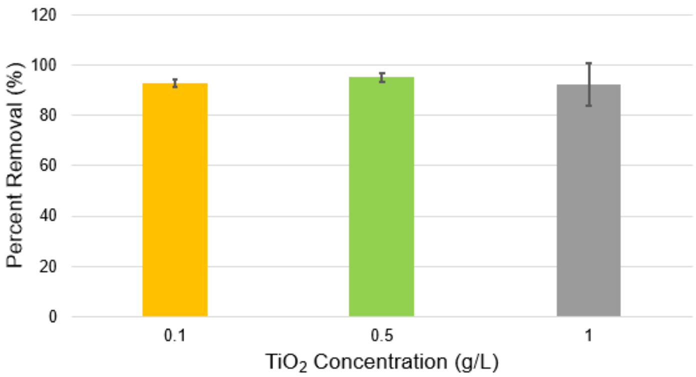


Figure 8. **The Effect of TiO_2 Concentration on Percentage of Dye Broken Down in Photocatalysis (n=3)**

Figure 8 shows that all groups were successful in breaking down dye, as they all had a removal rate of over 90%. The groups were not significant to one another when run through an ANOVA followed by a Post-Hoc Scheffe in SPSS, as the p-values were greater than 0.05. However, this is beneficial because it shows that even a small concentration of photocatalyst works as well as a large one.

Effect of Voltage

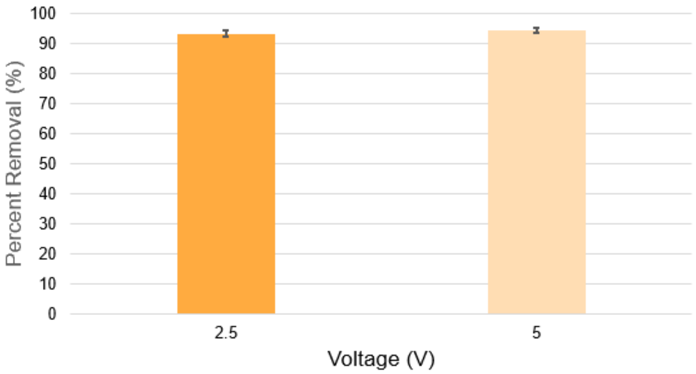


Figure 9. **The Effect of Input Voltage on the Percent Removal of Methyl Orange in Electrocoagulation (n=3)**

From Figure 9, it is demonstrated that while the percent of dye removed was slightly greater for the 5V group than the 2.5V group, the data was not significant. Both groups ended up removing nearly 95% of the dye when run for 20 minutes at their specific voltage. Again, this is a success because no matter the voltage inputted into the system, nearly all dye was removed.

3.4. Energy Generation Trials

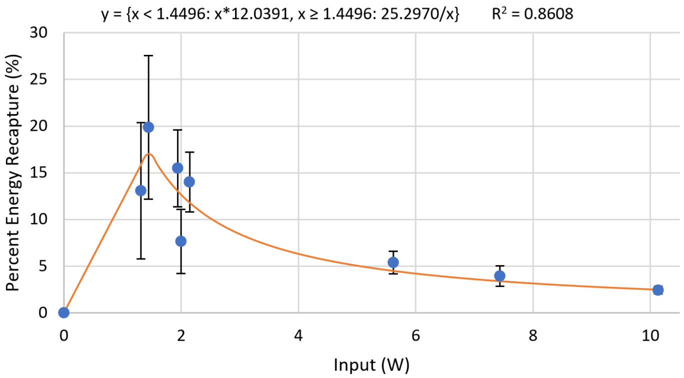


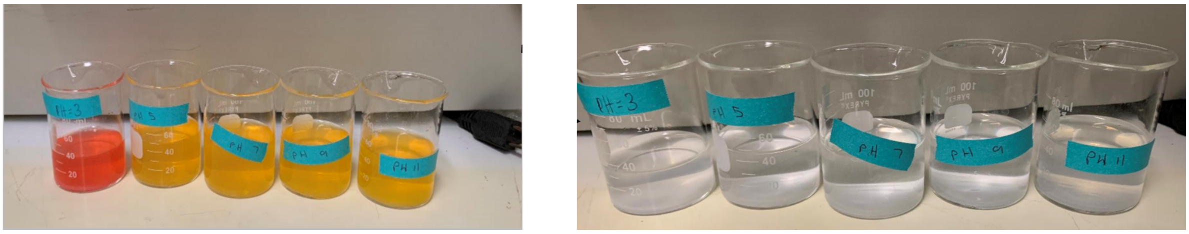
Figure 10. **Percent of Energy Recaptured in Electrocoagulation (n=3)**

From Figure 10, it is shown that the electrocoagulation process could recapture up to 20% of its energy, reaching a maximum with an input wattage around 1.5 W. In other words, the maximum amount of renewable energy that could be generated was 20% of the energy being put into electrocoagulation (doubling the hypothesis, and rendering the engineering goals a success). The efficiency spikes as the input voltage was raised from 0 to 1.5W, where the maximum flow rate of hydrogen was achieved, but then exhibits an inverse relationship when the input wattage was increased beyond this maximum value, because the output wattage levels off while the input wattage keeps increasing.

4. Discussion

The purpose of this study was to compare and optimize photocatalysis and electrocoagulation. pH, TiO_2 concentration, and dye concentration were tested for photocatalysis, and voltage, pH, and methyl orange concentration were tested for electrocoagulation. The study also sought to generate energy from H_2, a byproduct of electrocoagulation. The alternate hypothesis was partially supported, and the engineering goals were met, and in fact, exceeded.

Photocatalysis was successful, and was able to break down the vast majority of the dye at all pH values (Figure 11). It was most effective at pH values from 3 to 9, while pH 11 was significantly the least effective, as shown in figure 7. The results of Chen et al. in 2017 support this somewhat because that study showed that pH 11 is the least effective pH for dye breakdown. This was because the surface polarity of the photocatalyst switched from (+) to (-) at a pH between 9 and 11, which resulted in it being less able to attract the anionic methyl orange dye [9]. However, the results were somewhat contradictory, as in their study, acidic pH values worked the best, while pH 9 resulted in the greatest dye removal in this study. The difference may be a result of the photocatalyst used - Chen et al. in 2017 used ZnO as the primary catalyst [9], while this study used TiO_2. The differing band gaps and molecular structures between the two photocatalysts cause them to react differently at different pHs.



(a) Photocatalysis Trial Across all pH Values (Photo by Authors)

(b) The Same Trial, 24 Hours Later (Photo By Authors)

Figure 11. **A Photocatalysis Trial Before (a) and After (b) 24 Hours of UV Light Exposure**

There was also no significant change in photocatalytic efficiency as TiO_2 concentration increased (Figure 8), showing that relatively little amounts of TiO_2 are needed to purify water. These results are supported by Saggioro et al., in 2011, where the difference in dye removal between 0.1g/L and 1g/L was negligible [4]. Therefore, in real-life applications of photocatalysis, it is optimal to use lower concentrations of TiO_2, as removal rates will be similar, and less powder will then have to be removed.

The dye breakdown rate was high for the 50 and 100 mg/L of dye, but significantly lower for the group with a dye concentration of 150 mg/L (Figure 7). This makes sense, because a set amount of TiO_2 can only react with a certain amount of water and dye in a given time, so at some point, the concentration of dye becomes too large for the small amount of TiO_2 to fully break down in 24 hours. This point occurred somewhere between 100 and 150 mg/L.

Electrocoagulation was also successful, as it was able to coagulate the vast majority of the dye across nearly all operational parameters. The 2.5V and 5V groups were not significant to each other because both removed approximately 94% of dye (Figure 9). This was because the electrodes in both trials were at the same current density (40 A/m^2), so roughly the same amount of metal hydroxides were produced, since the amount of metal that dissociates from the anode and OH^- that is produced at the cathode is proportional to the rate electrons are transferred between the electrodes. This indicates that once a certain voltage is achieved, increasing it more does not have much of an effect. For pH testing, all groups resulted in the removal of nearly all dye, but they were not significant to one another (Figure 5). This is supported by Nandi et al., in 2013, who also found that dye removal rate was not significantly different in the pH range from 3-11 [2]. While pH does play a role in the process of electrocoagulation, electrocoagulation produces enough OH^- during the process to make metal hydroxides and coagulate most of the dye.

Lastly, for electrocoagulation, the group with a 150 mg/L initial dye concentration removed a slightly higher percentage of dye than the 50 mg/L or 100 mg/L group (Figure 7). This was because, unlike photocatalysis, electrocoagulation was able to produce enough metal hydroxides to remove most of the dye, at least up to 150 mg/L. Therefore, since all the final absorbances were roughly the same but the initial absorbances were greater for higher concentrations, the resulting removal rate was higher.

Electrocoagulation was more energy efficient than photocatalysis. Even though it required 11.18x more power (J/s) to run (0.335 J/s vs 0.030 J/s), it ran for a period of time 72x shorter than photocatalysis, making it 6.44 times more efficient. However, photocatalysis could potentially be run with only the light from the sun, while electrocoagulation requires a power supply.

The energy production design for electrocoagulation was able to collect a large amount of hydrogen, and the fuel cells produced a significant amount of power, resulting in a high energy recapture efficiency (Figure 10). The maximum percent of energy recaptured (20%) was nearly twice the hypothesis (11%). This means that in the future, the efficiency of electrocoagulation could be increased by 20%, which would have profound implications on the applicability of the process. In a broader sense, wastewater treatment and energy generation could happen at the same time, using only one design.

The 11% was hypothesized from a combination of previous research data about the amount of hydrogen generated from electrocoagulation [3] and fuel cell specifications. The fact it was doubled indicates success in the design, likely due to the fact that the study used two fuel cells rather than one. In essence, one fuel cell at its optimal amperage will generate less wattage than two fuel cells at half of their optimal amperages. This is because there is a roughly parabolic relationship between output amperage and output wattage in a PEM fuel cell, with the PEM fuel cell having a maximum output wattage at a certain amperage (Figure 12 - red curve) [11]. Because the slope of the graph decreases as amperage increases, the output wattage will rise more in the first half of the way to the practical maximum power than in the second half, making the wattage produced by two fuel cells at half the optimal amperage greater than the wattage produced by one fuel cell at the optimal amperage. The output amperage (the flow rate of electrons) of a PEM fuel cell is proportional to the rate of hydrogen flowing into the fuel cell. This means that, above a certain minimum hydrogen flow rate, the hydrogen stream can be split across multiple fuel cells to generate a greater total output wattage, which was observed in the study.

Using the cost of iron sheets as electrodes, the average cost of sludge collection, and the cost of electricity at the wattage that was used in this study's electrocoagulation trials, it was calculated that, if scaled up, wastewater treatment using electrocoagulation would cost between 0.112 to 0.147 cents per gallon. With hydrogen fuel cells, this would be brought down to 0.094 to 0.129 cents per gallon using the maximum recorded energy recapture efficiency of 20% (as this would decrease the net amount of electricity needed to be spent on the process). Conventional wastewater treatment ranges from 0.123 to 0.342 cents per gallon, with the average being at 0.206 cents per gallon [13]. With an average efficiency of 0.112 cents per gallon for electrocoagulation with hydrogen, this means this study's treatment method is on average 45% more cost effective than conventional treatment methods (Figure 13).

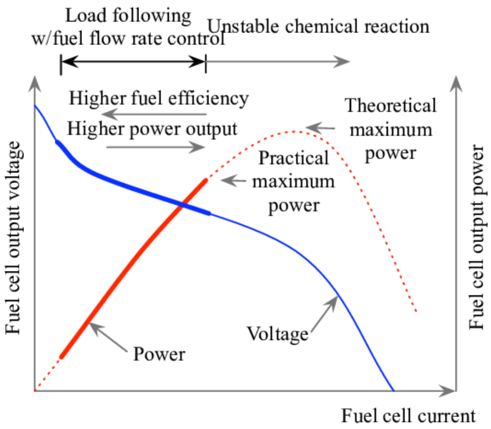


Figure 12. **PEM Fuel Cell Polarization Curve: Output Amperage on the X-Axis, Output Voltage in Blue, Output Wattage in Red (Graph By Lee et al., 2008 [11])**

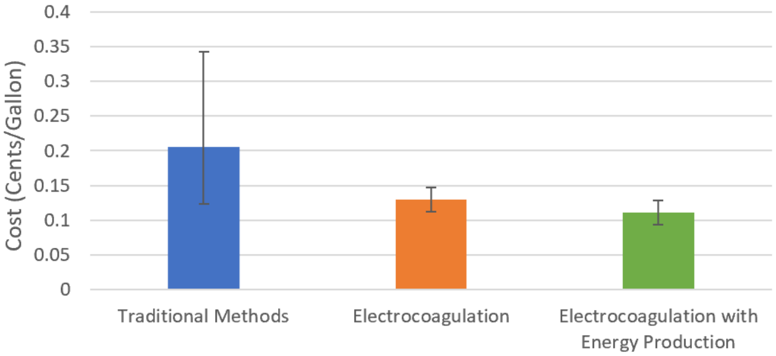


Figure 13. **A Cost Analysis of Methods to Treat Dye-Contaminated Wastewater**

This study is highly applicable in developing countries, where dye-contaminated wastewater is a major problem. As the sun releases UV rays, photocatalysis could easily be run using sunlight alone, provided the addition of only a tiny amount of catalyst (0.1 g/L or less), and the majority of dye would be removed in only 24 hours of daylight. While electrocoagulation does require a power supply, it can still be used to remove dye at a far lower cost than traditional methods. On top of that, energy can be generated from the waste products of electrocoagulation (H_2), allowing for the simultaneous removal of contaminants and production of renewable energy, addressing two environmental crises (contaminated rivers and over-reliance on fossil fuels) at once.

However, there are some limitations to this study. Photocatalysis was not tested with direct sunlight, so while it can be inferred that the process also works in ambient conditions (as the sun releases UV light), the study itself did not prove that. The process was also run on a small scale; we do not know how removal rates and hydrogen production rates would change when on an industrial scale. Finally, the hydrogen fuel cells had a small maximum output (roughly 2V), so it was difficult to know whether further increases in amperage would have resulted in greater energy recapture efficiency.

In the future, electrocoagulation could be run on a larger scale to generate more hydrogen, which would yield a better estimate of the efficiency increase on an industrial scale. Also, to better compare electrocoagulation to photocatalysis, electrocoagulation could be run using solar panels. This would mimic the light from the sun needed for photocatalysis. Finally, photocatalysis could be tested out in sunlight instead of in lab settings, to gain a better understanding of its real world implications.

5. Conclusions

1. Both photocatalysis and electrocoagulation could remove the vast majority of dye in water across almost all parameters, with the two processes removing up to 97.8% and 98% of the dye respectively.
2. The optimal conditions for photocatalysis were pH values between 3 and 10, a TiO_2 concentration between 0.1 and 1 g/L, and a methyl orange dye concentration 100 mg/L or less. For electrocoagulation, the optimal conditions were higher voltages, pH's between 3 and 11, and dye concentrations of 150 mg/L or less.
3. The engineering goals were successful; up to 20% of the energy could be recaptured, doubling the hypothesis (11%) due to the novelty of two fuel cells in the design. Both removal of dye and a lack of renewable energy can be addressed simultaneously using this study's electrocoagulation setup.
4. Electrocoagulation was more energy efficient than photocatalysis, but it requires a power source while photocatalysis can potentially run off only sunlight.
5. Electrocoagulation (especially with PEM fuel cells) was far more cost-effective than traditional wastewater treatments. This increases its potential applicability in real-world settings.

Conflict of Interest

Authors of this article declare that they have no conflict of interest.

Human Studies/Informed Consent

No human studies were carried out by the authors for this article.

Animal Studies

No animal studies were carried out by the authors for this article.

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