Removal of Methyl Orange Dye from Aqueous Solution Using Electrocoagulation System

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ABSTRACT

Access to freshwater is currently becoming more difficult, primarily as a result of population growth, the expansion of industry, and the lack of regulation over the various effluents in waterways. Wastewater that contains dyes is one of the main environmental hazards to freshwater. Methyl orange is one of the frequently used dyes, and lethal exposure to it can have serious negative effects on one's health and the environment.

In the current study, iron and steel electrodes were used to apply an electrocoagulation technique to the removal of the dye methyl orange from aqueous solutions under various conditions. Due to its simplicity, effectiveness, low cost, and lack of excessive chemical use, the electrocoagulation method was adopted. To determine how each parameter affected the dye removal efficiency, variations in the following parameters were examined: pH, initial methyl orange concentration, electrode distances, agitation speed, applied voltage, and electrolyte amount.

The results demonstrate that for both iron and steel electrodes, nearly 100% of 20 ppm methyl orange was removed in 20 minutes at pH = 3, electrode distance of 2 cm, electrolyte concentration of 0.75 g, applied voltage of 6 V, and stirring speed of 200 rpm. Additionally, the steel and Fe electrodes used 1.485 kWh and 1.683 kWh of electrical energy, respectively, and showed 62.99% and 79.61 % faraday electrode efficiencies. When the electrical energy used, the cost of the electrodes, and the chemicals to adjust the conductivity are taken into account, the operating costs to treat

1 m^3 of aqueous solutions containing 20 ppm of methyl orange were 0.45 USD for iron electrodes and 0.51 USD for steel electrodes.

The findings of this study are in line with previously published data that showed that increasing the applied voltage, electrolyte dosage, electrode distance, and pollutant concentration have an impact on the effectiveness of pollutant removal. The findings of this research demonstrate that the electrocoagulation approach can be successfully used to treat dye contaminated water when taking into account removal efficiency, treatment duration, ease of operation, and treatment cost. The generated sludge can also be characterised, modified, and conditioned for further use as an adsorbent or fertiliser.

Keywords: textile dye pollutants, electrocoagulation process, sludge, wastewater treatment.

ÖZ

Özellikle nüfus artışı, endüstrinin genişlemesi ve su yollarındaki çeşitli atık sular üzerinde düzenleme eksikliğinin bir sonucu olarak, tatlı suya erişim şu anda daha zor hale geliyor. Boya içeren atık su, tatlı su için ana çevresel tehlikelerden biridir. Metil turuncu boyası sıklıkla kullanılan boyalardan biridir ve buna ölümcül bir şekilde maruz kalmak kişinin sağlığı ve çevre üzerinde ciddi olumsuz etkilere neden olabilir.

Bu çalışmada, çeşitli koşullar altında sulu çözeltilerden metil turuncu boyasının uzaklaştırılmasına bir elektrokoagülasyon tekniği uygulamak için demir ve çelik elektrotlar kullanılmıştır. Basitliği, etkinliği, düşük maliyeti ve aşırı kimyasal kullanımının olmaması nedeniyle elektrokoagülasyon yöntemi benimsenmiştir. Her parametrenin boya çıkarma verimini nasıl etkilediğini belirlemek için şu parametrelerdeki varyasyonlar incelendi: pH, ilk metil turuncu boya konsantrasyonu, elektrot mesafeleri, çalkalama hızı, uygulanan voltaj ve elektrolit miktarı.

Sonuçlar, hem demir hem de çelik elektrotlar için, pH = 3, elektrot mesafesi 2 cm, elektrolit konsantrasyonu 0,75 g, uygulanan voltaj 6 V ve 200 rpm karıştırma hızında 20 ppm metil turuncu boyasının yaklaşık %100'ünün 20 dakikada giderildiğini göstermektedir. Ayrıca çelik ve Fe elektrotlar sırasıyla 1.485 kWh ve 1.683 kWh elektrik enerjisi kullanmış, sırasıyla %62.99 ve %84,5 faraday elektrot verimleri göstermiştir. Kullanılan elektrik enerjisi, elektrotların maliyeti ve iletkenliği ayarlayacak kimyasallar göz önüne alındığında, 20 ppm metil turuncu boyası içeren 1 m^3 sulu çözeltiyi işlemek için işletme maliyetleri demir elektrotlar için 0,45 USD ve çelik elektrotlar için 0,51 USD olmuştur.

Bu çalışmanın bulguları, uygulanan voltajın, elektrolit dozajının, elektrot mesafesinin ve kirletici konsantrasyonunun arttırılmasının kirletici uzaklaştırma etkinliği üzerinde etkisi olduğunu gösteren daha önce yayınlanmış verilerle uyumludur. Bu araştırmanın bulguları, elektrokoagülasyon yaklaşımının, uzaklaştırma verimliliği, arıtma süresi, kullanım kolaylığı ve arıtma maliyeti dikkate alındığında boya ile kirlenmiş suyu arıtmak için başarıyla kullanılabileceğini göstermektedir. Üretilen çamur ayrıca bir adsorban veya gübre olarak daha fazla kullanım için karakterize edilebilir, modifiye edilebilir ve şartlandırılabilir.

Anahtar Kelimeler: tekstil boya kirleticileri, elektrokoagülasyon prosesi, çamur, atık su arıtımı.

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LIST OF ABREVIATIONS

Al	Aluminium
BOD	Biochemical Oxygen Demand
C	Concentration
COD	Chemical Oxygen Demand
E.C	Electrocoagulation
Fe	Iron
KI	Potassium Iodine
MO	Methyl Orange
Na_2SO_4	Sodium Sulphate
NaCl	Sodium Chloride
Ph	Potential of Hydrogen
Ppm	Part Per Millions
Rpm	Round Per Minute
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
V	Volume

Chapter 1

INTRODUCTION

1.1 Water Pollution

All forms of life that we are aware of depend on water, which is also the universal solvent and helps carry out crucial chemical reactions (Lustenberg and Roberto, 2020). Only 3% of the water on Earth is freshwater, and 83% of that is either frozen glaciers or otherwise unavailable for human use (Bureau of Reclamation, 2020; World Wildlife, 2017), despite the fact that 70% of the planet is covered by water. In order to breathe, process food, irrigate farmland, and drink, humans need freshwater the most.

One-fifth of all people on the planet lack access to clean water. With population growth comes a rising need for access to clean water. The main issues with access to clean water are brought on by an uneven distribution of natural resources throughout the world and ongoing resource pollution from domestic discharges, agriculture, and manufacturing industries (Khemis, 2005). Along with human activity, arsenic and other naturally occurring pollutants in soils, such as those caused by geochemical processes, also contribute to groundwater pollution (Mollah et al., 2001).

Rapid industrialization since the middle of the 19th century has resulted in numerous significant environmental problems. Large quantities of persistent organic pollutants from industrial wastewater are released untreated into open water, causing pollution and the deterioration of water bodies.

Water availability and sustainable management of water and sanitation for all people were designated as the sixth Sustainable Development Goals by the United Nations in 2010 (Lustenberg and Roberto, 2022). As a result, it is urgent to develop techniques and technologies that protect, preserve, and purify water. Numerous dedicated researchers have explored and created sustainable solutions for water treatment in an effort to aid in the resolution of this water dilemma.

Figure 1:Different sources of water pollution

1.2 Textile Wastewater

According to Chandanshive et al. (2020), over 10,000 tons of synthetic dyes are used by the textile industry each year, out of the 7×10^7 tons that are produced annually globally. Dyes are often divided into several categories according to their origin, structure, and application (Tohamy et al., 2022; Akpomie and Conradie, 2020). According to their origin, structure, and intended use, dyes are frequently categorised

into a number of groups (Tohamy et al., 2002; Akpomie and Conradie, 2020). Figure 2 illustrates the various synthetic dyes that are used by the textile industry, including reactive, azo, mordant, disperse, direct, acid, basic, and sulphide dyes.

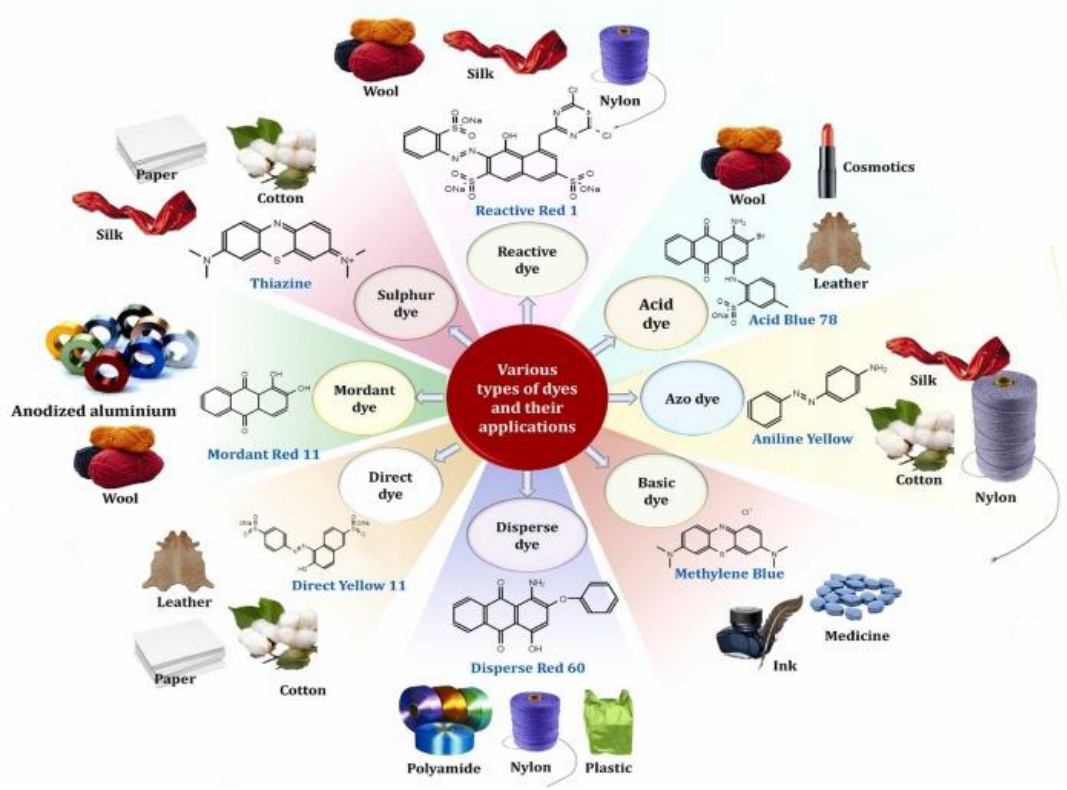

Figure 2:Various dye categories and potential industrial uses (Tohamy et al., 2022)

In the textile industry, dyes are frequently used to create stunning and vibrant textiles. The textile industry uses a lot of water during production and processing of textiles and fabrics for the pre-treatment of fabrics, dyeing, printing, and washing, resulting in wastewater with dye concentrations as high as 15% (Safa and Bhatti, 2011). The presence of dyes and textile pigments in wastewater causes it to be highly coloured, with a variable pH, low levels of dissolved oxygen, and high levels of biological oxygen demand, total organic carbon, chemical oxygen demand, and suspended solids (Tohamy et al.,2022).

The majority of environmental pollutants from the textile industry are resistant to aerobic media's natural processes, making them difficult to transform. According to Vikrant et al. (2018), this recalcitrance leads to the bio-agglomeration and transport of pollutants in the waterways. The textile industry's wastewater flow sheet into storage or direct discharge into bodies of water is depicted in Figure 3.

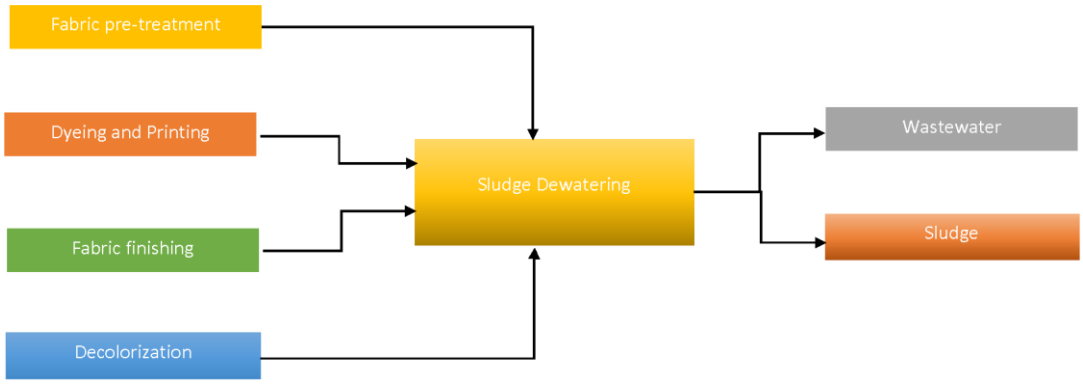

Figure 3:Shows a flowchart for the textile industry's wastewater

The largest class (above 60%) among the various groups of textile dyes and the most popular dyes in the textile industry are azo dyes, which structurally contain one or more azo groups (Tohamy et al., 2022). Ineffective textile dyeing methods, according to Singha et al. (2021), cause 15–50% of azo dyes to be released into produced wastewater that are not bonded to fabrics and fibres. While some textile industries filter their wastewater to remove free azo dyes from the environment, others dump industrial effluent directly into water bodies, creating major ecotoxicological hazards as well as toxic impacts on living creatures.

Methyl orange (MO), often known as a pH indicator, is one of the most widely used water-soluble azo dyes and is utilised in a variety of sectors. Figure 4's representation of MO's structure includes a number of attached elements as well as the azo group that

connects the structural units. MO dye poses serious risks to the environment and public health due to its recalcitrant nature, difficulty in degrading, and potential release into soil and aquatic resources (Robati et al., 2016).

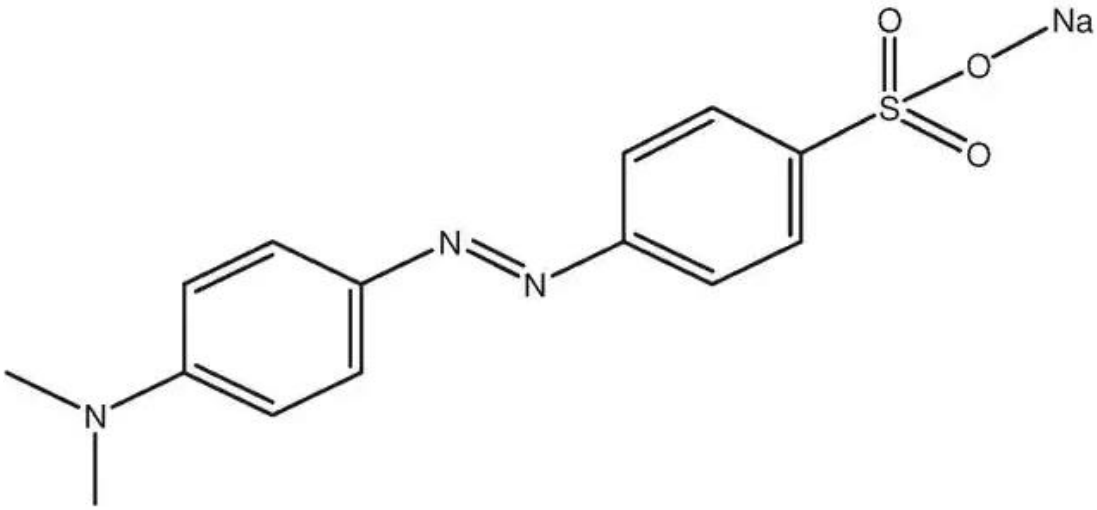

Figure 4: Structural formula of methyl orange dye, a commonly used azo dye

1.3 Wastewater Treatment Technologies

Despite their importance in the textile industry, the use of dyes leads to a lot of environmental problems. Despite being crucial to the textile industry, dye use has a negative impact on the environment. There are numerous techniques for treating textile dye wastewater, which can be categorised as mechanical, biological, and physicochemical techniques, as shown in Figure 5.

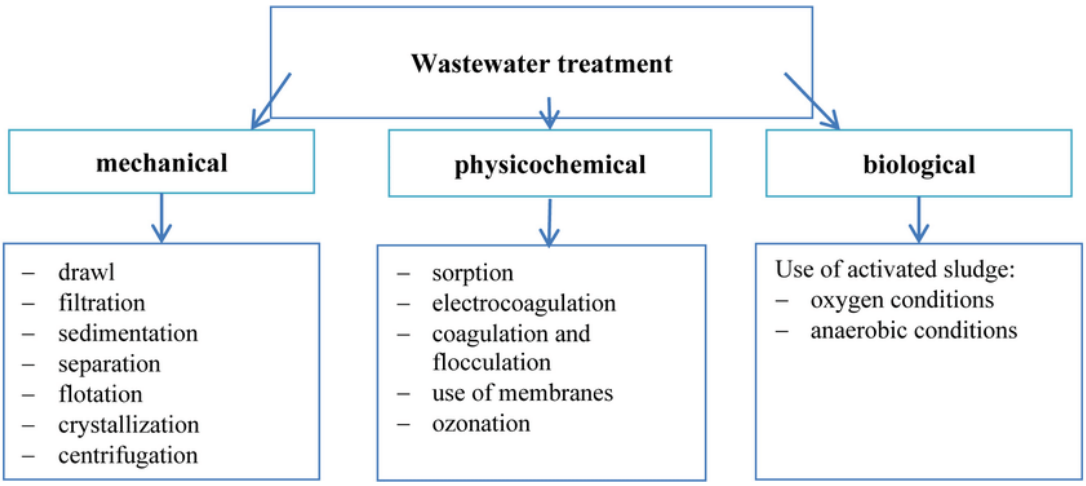

Figure 5: Technologies for treating wastewater

1.3.1 Biological Treatment

Because it is a relatively inexpensive process, the biological method is frequently used to treat wastewater. Biological treatment can be carried out either with oxygen present (aerobic process) or without oxygen present (anaerobic process). Organic compounds are broken down by microorganisms into carbon dioxide and water in aerobic processes, whereas pollutants are broken down into methane and carbon dioxide in anaerobic processes. These two approaches are combined to produce effective results for a biological process (Mahmoud et al., 2018).

Even though it is less expensive than other traditional methods, biological treatment alone cannot completely remove all dyes from wastewater. Recalcitrant dyes frequently kill microorganisms, and the majority of dye pollutants are not biodegradable. The conventional biological approach takes time as well. Other biological techniques, such as adsorption by microbial biomass, algae degradation, enzyme degradation and fungal cultures are more practical for dye removal than conventional biological techniques (Kathereson et al., 2018).

1.3.2 Coagulation and Flocculation

Coagulation and flocculation are used in the pretreatment process of water treatment. The pretreatment stage of water treatment involves the use of coagulation and flocculation. Here, a suitable coagulant is mixed with the wastewater to produce a compound that can be quickly separated from the water medium. As a result of this process, flocs are created, which precipitate at the cell's bottom and are subsequently sedimented out of the water. Aluminium sulphate, ferrous sulphate, ferric chloride, and chitosan are the most frequently used coagulants (Hassan, 2020). The steps of the coagulation and flocculation processes are shown in Figure 6.

The destabilised molecules aggregate into micro flocs during the flocculation process, which is a step in the coagulation process. Larger flocs are eventually formed when the smaller ones combine, and they decant. And then, the micro flocs agglomerate to form larger flocs and decant. To obtain a significant number of decants, the system may need to be supplemented with a flocculating agent (Zongo, 2009).

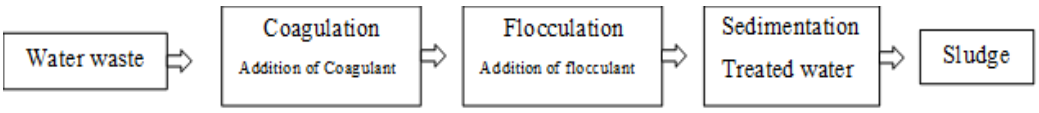

Figure 6: Illustration of the chemical coagulation method

1.3.3 Adsorption

The adsorption process is a surface phenomenon that involves the pollutant's (adsorbate's) adhering or attachment to the surface of a solid adsorbent material. Heavy metals, organic and inorganic compounds, dyes, and agricultural pollutants can all be treated using the adsorption method. Physical forces or/and chemical bonds may be responsible for the transfer of pollutants from liquid media to adsorbent surfaces.

The most widely used adsorbent is activated carbon because of its high porosity and large surface area. In addition to activated carbon, other natural polymers and biocomposites are being developed due to their advantages of being biodegradable, eco-friendly, accessible, and easily modified to improve the adsorption performance.

1.3.4 The Advanced Oxidation Process

In advanced oxidation processes (AOPs), reactive and highly oxidising radicals are generated in order to dissociate the chemical bonds that hold pollutants' molecules together. According to Amor et al. (2019), AOPs typically lead to the formation of less toxic intermediates or/and mineralized compounds like H_2O, CO_2, sulphate salt, nitrogen salt, and phosphate salt.

Ozone, catalysts, hydrogen peroxide, persulfate, and energy sources are sources for common radical generation. Sulphate and hydroxyl radicals are the most frequently used radicals due to their selectivity, high oxidation potential, and reactivity. The AOP uses homogeneous or heterogeneous catalysts that can be activated by light (photocatalysis), sound (sonocatalysis), electricity (electrocatalysis), or a combination of these processes. In a heterogeneous system, the catalyst is solid and the pollutants are liquid, whereas in a homogeneous system, the catalyst and the pollutants are in the same phase.

The advanced oxidation process has the benefits of using fewer chemicals, having a high capacity to degrade a variety of organic pollutants that are resistant to degradation, and not producing any sludge.

In this study, dye-polluted water was treated using the electrocoagulation method under a variety of reaction conditions. This is based on the fact that electrocoagulation

has, to the best of my knowledge, been used in fewer studies to treat textile dye wastewater, in addition to being simple to operate and relatively inexpensive. In the following chapter, electrocoagulation's benefits and mechanisms are thoroughly discussed.

1.4 Thesis Objectives

The following are the goals of this thesis:

- To treat water contaminated with methyl orange dye by electrocoagulation.
- To investigate how various parameters, including electrolyte dosage, electrode distance, treatment time, solution pH, and current density, affect how well an electrocoagulation system works.
- To investigate how iron and steel electrodes perform when treating dye-contaminated water.

1.5 Thesis Limitation

The following are this work's limitations:

- Rather than actual wastewater from the textile industry, synthetic dye-contaminated wastewater was used in all of the experiments for this thesis.
- A 200 mL laboratory-scale EC cell was used; an industrial- or field-scale version has not been tested.
- Additionally, electrode geometry and arrangement both play important roles in the EC process, but this research only examined one type of arrangement and made no modifications to electrode geometry.

Chapter 2

LITERATURE REVIEW

2.1 Theory of Electrocoagulation

In an electrochemical cell, the electrocoagulation (EC) technique combines the benefits of coagulation, flotation, and electrochemistry to treat water containing a variety of pollutants, including dyes, organic compounds, viruses, heavy metals, and dissolved and suspended particles. Due to the mobility of electrons in the electrolytic solution, electrocoagulation processes involve two reactions at the electrodes (cathode and anode) (Bharath et al., 2018). Sacrificial anodes dissolve as a result of oxidation at the anodes. Hydroxide ions and hydrogen gas are created when water is reduced at the cathode. According to Picard et al. (2000), electrocoagulation was first applied to the treatment of wastewater in the USA in 1880. In the same year, a second plant for the electrocoagulation method of effluent treatment was constructed in the United Kingdom (Zodi et al., 2012). According to Kolt et al. (2002), aluminium electrodes were used in the electrolytic cell to develop the electrocoagulation procedure in 1946. Bennajah et al. (1947) found that electrochemical methods outperform coagulation and flocculation methods in the treatment of wastewater containing small particles. Due to its lack of chemical use and low process cost, EC research gained more attention in the 1970s and began to enjoy greater privileges than chemical methods (Nemr et al., 2011).

In order to perform an electrocoagulation procedure, a reactor with two electrodes—an anode and a cathode—connected to an external power source is required (Yousuf et al., 2000).

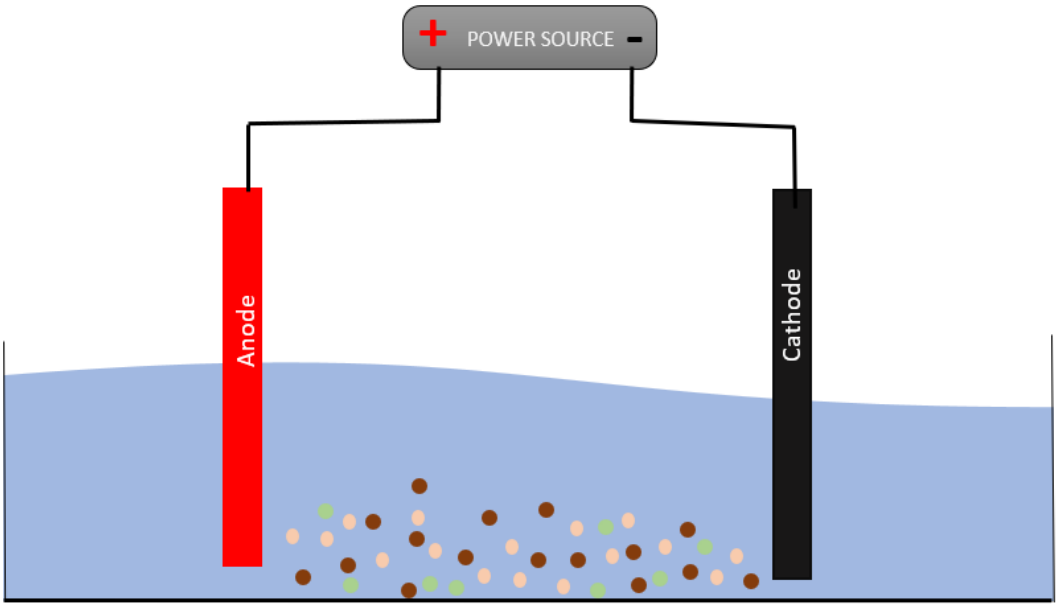

Figure 7: Electrocoagulation reactions

In this electrochemical process, the anode dissolves when current flows through it, destabilising the pollutants and forming an aggregate that can be easily separated by filtration. Any type of pollutant, including heavy metals, organic compounds, dyes, and microorganisms, can be eliminated using this method. The EC method works by dissolving a sacrificial anode that combines with pollutants to form an aggregate (Segura et al., 2017). This aggregate is then removed from the water.

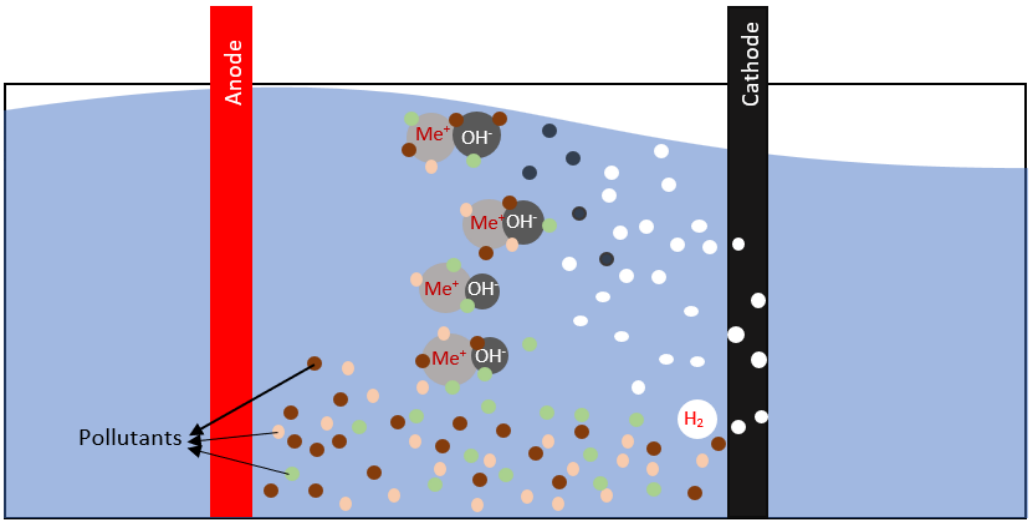

Figure 8: Destabilisation of pollutants

According to Mollah et al. (2004), the E.C process was used to treat orange II dye with a concentration of 10 ppm; at a pH of 6.5 and a current density of 160 A/m^2, the system was able to remove 94.5% of pollutants. Zongo (2009) also investigated removal of the textile dye using the E.C process, by coating iron on wire as the anode and cylindrical iron as the cathode. The study concentrated on significant variables like voltage, turbidity, current, and COD. According to the results, 96.9% of the COD was removed while the wastewater's colour had been completely eliminated.

Zheng et al. (2012) used RuO_2 as an anode in the treatment of synthetic wastewater containing dye. They came to the conclusion that the elimination of the pollutant is easier at low initial concentration and low pH after achieving the elimination of 42.3% of pollutants after 5 minutes. Gomes et al. (2007) used iron electrodes to remove 99.6% of the heavy metals, and they used aluminium electrodes to remove 78% of the heavy metals. For the purpose of removing BOD and COD, cigarette manufacturing wastewater was treated by E.C. using iron electrodes by Bejankiwar (2002). The findings revealed that 56% of COD and 84% of BOD were eliminated. When Raju et

al. (2008) used iron and aluminium electrodes to remove COD and suspended solids from textile effluent, they were able to remove 96% of the TSS and 62% of the COD. Drogui et al. (2007) used a combination of iron and steel electrodes to effectively treat dye solutions, removing 100% of the colour and 75% of the COD.

El-ashtoukhy et al. (2010) used aluminium electrodes oriented at random in the electrolytic cell to investigate the effectiveness of electrocoagulation to remove phenolic compounds. Using 1 ppm sodium chloride, 25 °C, and 8.59 A/cm^2 of current density, the system achieves its best performance at pH = 7. Domestic wastewater was treated using an electrochemical process by Pouet and Persin (1995). Following microfiltration of the treated water, turbidity, COD, and TSS removal reached 30%, 20%, and 65%, respectively, demonstrating the system's ability to remove COD, suspended particles, and turbidity.

E.C. was used by Taweel et al. (2013) to treat wastewater from petrochemical production. The investigation focused on removing phenols, hydrocarbons, and turbidity. After two hours, the electrochemical reactor's perforated plastic cathode and aluminium anode were able to completely remove the phenol compound at a current density of 8.5 mA/cm^2, a pH of 7, a NaCl concentration of 1 g/L, a temperature of 25 C, and a concentration of 3 mg/L. Naraghi et al. (2019) used iron electrodes to remove 96% of the colour from reactive dye wastewater using the E.C process, at pH = 6, voltage = 30V, initial concentration = 89.5%, and time = 80 min. Seyed et al. (2017) compared the efficacy of iron and aluminium electrodes for the adsorption of Remazol black dye. According to the findings, iron electrodes removed 99.4% of the colour while aluminium removed 91%.

By electrocoagulation with aluminium electrodes, Vidal et al. (2016) completely eliminated acid black 194 in a brief period of time. Anmol et al. (2016) used iron electrodes to electrocoagulate completely brilliant green, bromo blue, and brilliant blue dye.

2.2 Advantages of Electrocoagulation

E.C. technology provides a wastewater treatment alternative with a number of benefits, including:

1. Simple equipment.
2. Pollutants can be completely removed.
3. It is non-selective, i.e., it can remove all types of pollutants.
4. The process results in less sludge being produced.
5. No chemical usage.
6. Sludge is recyclable.
7. There is a lower chance of secondary pollution.
8. It is simple to remove EC sludge.

2.3 Disadvantages of Electrocoagulation

1. There are some locations where the cost of electricity is high.
2. Since sacrificial anodes deteriorate over time, they must be frequently replaced.
3. The E.C process could result in unexpected in-situ reactions.
4. An electrolyte is necessary if the wastewater has a low conductivity.
5. An oxide film forms at the cathode, which reduces the output of hydrogen gas.

2.4 Mechanism of Electrocoagulation Technique

Electrochemical reactions occur in the system when electrical current is present. The mechanism involves the dissolution of anode. By permeating the mixture, the ionic

coagulants produced destabilise the emulsion and make it easier for pollutants that are suspended or dissolved to form clusters.

The steps involved in the electrocoagulation process are as follows:

1. Metal cations are produced when sacrificial anodes are oxidised at the anodic site.
2. The reduction of water at the cathode results in hydrogen gas and hydroxide ions.
3. Metal hydroxide is created when the produced hydroxide ions combine with cationic metals.
4. These metal hydroxides combine with pollutants to destabilise them and form an aggregate.
5. Depending on the pH, aggregation takes the form of either a float or a decant in the cell.
6. Either flotation or decantation are used to remove aggregates.

2.4.1 Possible Reactions: Iron as the Electrode

Reactions when iron oxidises into Fe^{2+}

Anode: $Fe\ (s) \rightarrow Fe^{2+} + 2e$

Cathode: $2H_2O + 2e \rightarrow 2OH^- + H_2$

Overall reaction: $Fe\ (s) + 2H_2O \rightarrow Fe(OH)_2$

When it oxidises into Fe^{3+}

Anode: $Fe\ (s) \rightarrow Fe^{3+} + 3e$ and $4\ Fe^{2+} + 10\ H_2O + O_2 \rightarrow 4\ Fe(OH)_3 + 8\ H^+$

Cathode: $8H^+ + 8e \rightarrow 4H_2$

Overall reaction: $4Fe + 10\ H_2O \rightarrow 4Fe(OH)_3 + 4H_2$

2.4.2 Possible Reactions: Aluminium Electrodes

Anode: $Al \rightarrow Al^{3+} + 3e$

Cathode: $3H_2O + 3e \rightarrow 3OH^- + 3/2\ H_2$

Global reaction: $Al + 3H_2O \rightarrow Al\ (OH)_3 + 3/2\ H_2O$

2.5 Effect of Operating Parameters

Initial concentration, pH, electrode distances, electrode arrangements, amount of electrolyte, current density, and applied voltage are all crucial operating parameters. In order to treat pollutants as yield at a price that is economically profitable, the operator must be able to control these effects.

2.5.1 Effect of Initial pH

One crucial parameter that we must take into account is the initial pH. The solution conductivity, electrode dissolution, and formed species are all impacted by the pH of the effluent during E.C treatment. Depending on the pH of the medium, different species of Al or Fe can form when anodes (such as iron or aluminium) dissolve. The pollutants can then be effectively removed by combining these species with pollutants to create aggregated sludge. After the experiment, the generated sludge will need to be characterised in order to determine the species that were formed and to develop a removal method for these pollutants (Malakootian et al., 2012).

2.5.2 Effect of Initial Pollutants Concentration

When pollutants are concentrated in wastewater, removal efficiency decreases; conversely, when pollutants are less concentrated while maintaining the same current density, removal efficiency increases. The explanation for this is that at high concentrations, the anode's ions do not produce enough ions to coagulate with all pollutants (Dalvand, 2011). When the concentration of 4-nitrophenol was 15 ppm, as demonstrated by Marshals et al. (2011), the removal efficiency was 99.9%; however, when the concentration was 35 ppm, it decreased to 88.7%.

2.5.3 Effect of Electrolytes

By ionising during the flow of current, an electrolyte raises the conductivity of the mixture. In E.C. technology, a variety of electrolytes are employed, including NaCl,

Na_2SO_4, and KI (Saha et al., 2017). Due to the different ionic species, an electrolyte has a greater effect on wastewater contaminated by a single pollutant than it does on wastewater contaminated by a number of compounds. Inhibitory secondary reactions may also occur with electrolytes. For instance, some salts may precipitate at the cathode at high concentrations. Some ions, like CO_3^-, or SO_4^{2-}, can interact with calcium or magnesium ions to form a layer that prevents an anode from dissolving (Ghernaout et al., 2018).

2.5.4 Effect of electrodes' Shapes and Electrode Materials

Numerous studies have found that compared to other electrode shapes, plane electrodes have a higher removal efficiency (Khandegar and Saroha 2012). According to research by Kobya et al. (2015), ball electrodes only removed 96.3% of the arsenic while plane electrodes removed 99.3%.

According to Bouhezile et al. (2011), the choice of an electrode material is influenced by its price, availability, EC efficiency, and anodic dissolution. In numerous studies, the E.C. process employs a variety of metals as electrodes, including:

1. Aluminium
2. Zinc
3. Stainless steel
4. Iron
5. Graphite.

2.5.5 Effect of Inter Electrodes Distances

The distance between the electrodes is also crucial; as the inter-electrode distance increases, the efficiency of the E.C. process declines, and vice versa, because at a close distance, more ions collide with passing electrons, reducing resistance. Be aware that

if the distance between the electrodes is too small, the process may result in a short circuit (Khandegar and Saroha 2012).

2.5.6 Effect of Electrodes Arrangement

The performance of the E.C reactor is significantly impacted by how the electrodes are arranged based on different configurations. Monopolar or bipolar electrode arrangements are both possible. According to Ding et al. (2002), an electrode arrangement is monopolar if electrodes with the same polarity (sign) are connected, and bipolar if only the two terminals, cathode and anode, are connected to a power source and the other electrodes are polarised by the flow of current in the cell.

The equivalent resistance of a series connection of monopolar electrodes is equal to the total resistance of the materials, which results in a very large potential difference. The same current flows through the cell in a series connection. The following illustration depicts an E.C cell with electrodes connected in series.

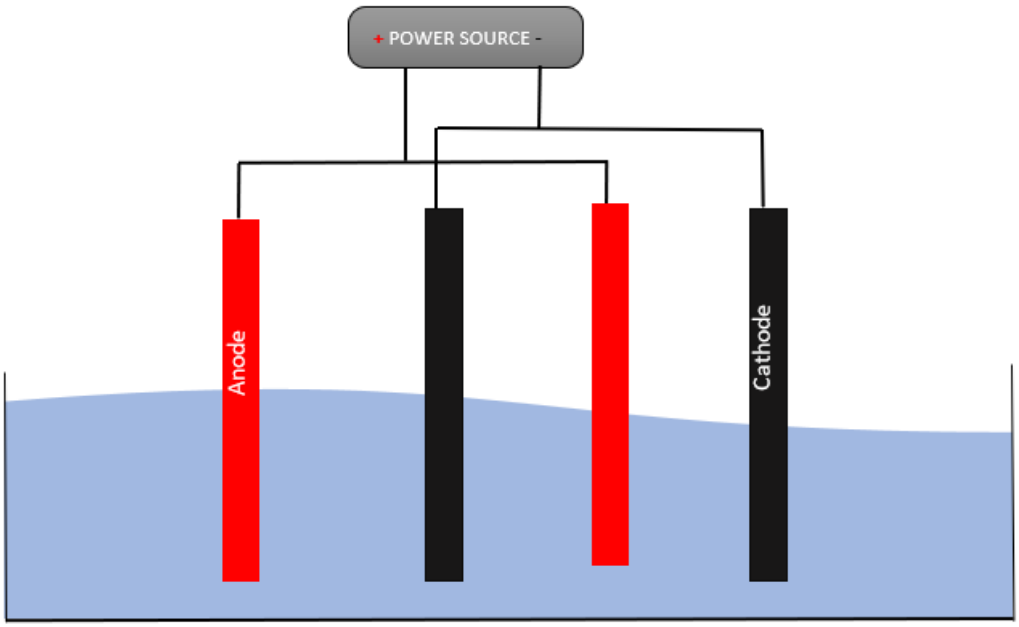

Figure 9: Monopolar electrodes in series

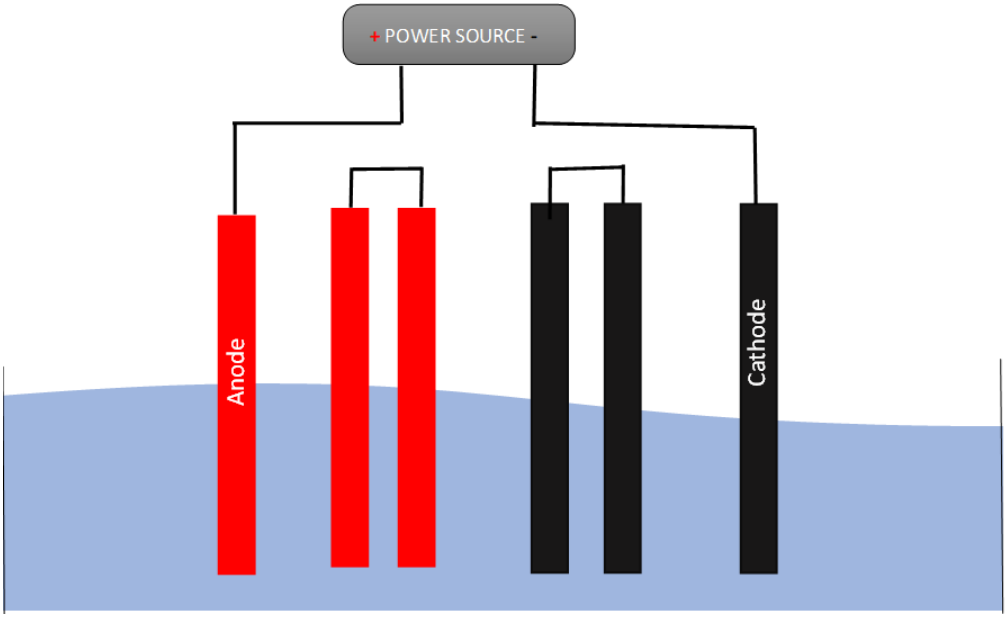

Figure 10: Bipolar electrodes in parallel

The total electric intensity is split between the number of electrodes in bipolar parallel arrangement. Sacrificial anodes that are connected in parallel between two bipolar electrodes experience oxidation reactions, whereas reduction reactions are seen at the cathodes. The figure 10 above shows an arrangement of parallel bipolar electrodes.

2.5.7 Effect of Power Supply

Both direct current (DC) and alternative current (AC) power sources are usable during electrocoagulation. According to Yang et al. (2015), the direct current mode is a type of current in which the frequency of the current changes after a regular period of time, whereas the alternative mode is a type of current in which the frequency of the current changes continuously. According to reports, the alternative current mode is more effective for the electrocoagulation process because it reduces EC yield and prevents electrode passivation (Vasudevan et al., 2011). During passivation, an oxide layer is created around the cathode, typically using the dissolved anode as a starting point. The movement of electrons is slowed down by this layer. It is possible to prevent the

formation of layers by using an alternative current with a variable frequency (Ahmad et al., 2016).

2.5.8 Effect of Agitation Speed

Permanent magnetic agitation is useful in the electrocoagulation process because it prevents gradients of concentration in various parts of the system. Generally speaking, an increase in the rate of agitation causes an increase in the system's reaction rate. It should be noted that agitation levels above the optimum level can reduce the effectiveness of the E.C. process because prolonged agitation can dissolve coagulants that form early in the system (Khaled et al., 2019).

2.5.9 Effect of Current Density

The ratio of the cell's current density to the anode's effective surface area is known as the current density. Because it controls the size and growth of flocculants as well as the rate at which coagulants form, current density is a crucial factor in the EC process. The anode dissolves faster when the current density is higher. As more anode is dissolved over time and more coagulant species are created in the system, the process becomes more efficient. According to Lakshmi et al. (2013), there is a current density optimum beyond which it will not have an impact on the process' rate due to secondary reactions.

2.6 Removal Efficiency of Pollutants

The ratio between the pollutant concentration that was removed and the pollutant's initial concentration in the wastewater is used to measure the effectiveness of pollutant removal.

$$R\ (\%) = \frac{Co - Cf}{Co} \times 100 \qquad \text{(Eq. 1)}$$

Where Co= initial concentration and C_f = final concentration.

2.6.1 Operating cost Analysis

The goal of each step in the process must be to produce a result with the lowest possible economic cost. The following factors are the main drivers of electrocoagulation process cost:

1. Cost of electrodes.

2. Cost of energy consumption.

3. Sludge disposal.

4. Other fixed expenditures.

Operating cost= a $C_{electrodes}$ + b C_{energy} (Eq. 2)

Where $C_{electrodes}$ is the consumption electrodes, and C_{energy} is the consumption n energy per litre of water treated. a = unit price of electrodes and b = unit price of energy.

Celectrodes= $\frac{i.t.M}{F.Z}$ (Eq. 3)

Where,

M= molar mass.

F= Faraday constant.

Z= number of electrodes

Cenergy= $\frac{U.i.t}{V}$ (Eq. 4)

Where,

U= applied voltage.

i= current in ampere (A).

v = volume of cell.

t= electrolysis time.

2.7 Application of Electrocoagulation Technology

2.7.1 Effluents containing Hardness

About 50% of the world's population uses groundwater. The majority of the time, groundwater will be hard, which will prevent it from being used for domestic and some industrial purposes (Kumbhare, 2022). By electrocoagulating hardness-containing drinking water with iron electrodes over a period of 60 minutes, Mansoorian et al. (2010) were able to remove 97.4% of the hardness at pH=10 and voltage=12V. The removal of total hardness by electrocoagulation was studied by Saravan et al. (2014). Groundwater with a hardness concentration of 883 mg/L was treated using aluminium electrodes, and the procedure effectively removed 60% of the hardness at a pH of 7.38 over the course of 60 minutes while using 20V of voltage.

2.7.2 Industrials Effluents Containing Metals

Metals found in water, such as arsenic, cobalt, copper, lead, and iron, can be fatal in high concentrations. According to Martins et al. (2012), electrocoagulation was used to treat synthetic wastewater containing heavy metals: Current efficiency, electrolyte concentration, time, and energy consumption were all examined. An 8.0 current is applied over a prolonged period of time to complete the process. According to Bazrafshan et al. (2008), it takes between 20 and 60 minutes to reduce chromium (VI) solutions to levels below the regulated limits. For the system, iron electrodes were used in place of aluminium electrodes. According to Fangs' (2008) treatment of Cu^{2+} and Cr^{6+} using iron and stainless electrodes, 93% of Cu^{2+} and 98.91% of Cr^{6+} were removed at pH=4, time = 30 minutes, and Voltage = 4V.

2.7.3 Oily Effluents

Domestic sources of oily wastewater include bathrooms and kitchens, while commercial sources include the petrochemical, food processing, and soap

manufacturing industries. Oils in natural water sources inhibit the photosynthesis of marine plants, raise BOD and COD, and lower the amount of free oxygen (Diaz et al., 2006). Electrocoagulation was used to treat oily wastewater by Panikulam et al. (2015), who came to the conclusion that it is a cost-effective method of doing so. Younker et al. (2011) used an electrocoagulation process to remove 62% of COD from synthetic oily wastewater.

2.7.4 textile Industry Dye

The majority of textile effluents contain dyes. Dye exposure leads to human cancer and is not biodegradable in the environment. In natural water sources, dye-containing wastewater reduces the light that penetrates the sea and affects the ecosystem of water sources. Aquino et al. (2014) used electrocoagulation with Ti-Pt/PbO_2 electrodes to remove all colour and 86% of COD in 180 minutes. The current density was 75 mA/cm2. At pH = 2 and 3 g/L of NaCl as an electrolyte, 100% of COD was completely removed from textile wastewater by Zou et al. (2017) in 180 minutes.

Chapter 3

EXPERIMENTAL STUDY

3.1 Reagents and Materials

Analytical grades of compounds are utilised throughout. Methyl orange, which has a molar mass of 327.33 g/mol was purchased from Merck KGaA in Darmstadt, Germany, as well as sodium chloride, NaOH (>99%), and HCl (37%). The two sets of iron and steel electrodes that were employed in this study were acquired from a mechanical workshop in Famagusta, North Cyprus. Chloride sodium (NaCl) was used as a supporting electrolyte.

3.2 Experimental

3.2.1 Preparation of Stock and Working Dye Solutions

A stock solution containing 100 mg/L was prepared by combining 0.05 g of methyl-orange dye with 500 mL of distilled water. The stock solution of methyl orange was diluted to achieve the necessary methyl orange concentrations, and the serially diluted methyl orange solution was used to create the calibration curve. 0.1 M hydrochloric acid and 0.1 M sodium hydroxide were used to adjust the pH of the methyl orange solution to the appropriate level.

3.2.2 Analytical Method

The pH and conductivity of the dye were measured using an inoLabpH/cond 720 pH metre (Germany). The electrocoagulation system was powered using a DC power system (MH03819, Frederiksen Denmark) with adjustable current and voltage knobs. After each experimental test, the absorbance of the methyl orange at 465 nm was

obtained using a UV-Vis spectrometer (UV-1201V, Shimadzu, Japan). The produced sludge was dried for 24 hours in a conventional oven before being analysed with a PerkinElmer FTIR UATR two spectrophotometer.

3.3 Experimental Setup and Procedure

3.3.1 The Electrocoagulation Reactor

A rectangular cylinder measuring 7 cm x 4 cm x 30 cm served as the electrolytic cell for this study. During the procedure, steel-steel and Fe-Fe electrode pairs were used. On supports, the electrodes were positioned 2.5 cm above the reactor's base. The system is mounted in a way that allows the electrode spacing to be adjusted from 1 cm to 7 cm. Throughout the experiment, the solution was stirred by a magnetic stirrer at the bottom of the cell. The range of stirring was 100-400 rpm. The following picture shows the setup of an electrocoagulation system.

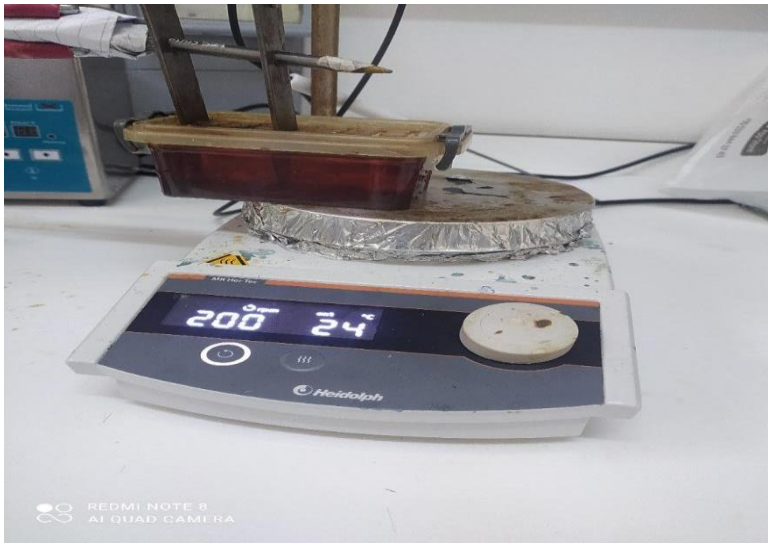

Figure 11: Electrocoagulation setup

3.3.2 Electrocoagulation Process

The dimensions of the two iron electrodes that were used were 15.8 cm in length, 2.45 cm in width, and 0.35 cm in thickness. Steel electrodes have the following dimensions: 16 cm long, 3.4 cm wide, and 0.1 cm thick. To prepare them for use, each electrode was first cleaned with a hard sponge to remove dust and then submerged for one minute in a 1 M chloride acid solution to prevent electrode passivation brought on by oxide deposit. Electrodes were submerged in acid and then later cleaned with distilled water, dried, and weighed before the experiment began. At the end of each process, the electrodes were washed again and weighed in order to measure anode weight loss. The electrodes were once more washed after each procedure, and their weight was recorded to determine the anode's weight loss.

The system includes a plastic electrolytic cell with two electrodes that is connected to the power source by a direct current circuit, as shown in the above diagram. One electrode is anode and the other one is cathode, to maintain the homogeneity of solution, the process is working under a magnetic stirring. Each reaction was started by adding sodium chloride to the solution as an electrolyte, and it was carried out at room temperature. Two electric wires connected the two electrodes to the energy source. The electrodes protruded from the cell at a length of 2 cm. Through the use of an adjustment knob, the applied voltage was adjusted to the desired level.

The amount of energy used during the process depends on how long it takes and how much amperage is measured. Each process' duration was recorded using a digital stopwatch. After every experiment, the treated wastewater was filtered using filter paper after being allowed to settle for a while. The filtrate was analysed using a UV-vis spectrophotometer at 465 nm while the sludge was dried in an oven at 40 ^{o}C. Each

of the parameters in the range listed in the following table was examined for their impact on the efficiency of electrocoagulation.

Table 1:Values of parameters used in this study

Parameters	**Values**
pH	3–11.
Treatment time	5 – 60 minutes
The concentration of pollutant	5, 10, 20, and 30 mg/L
Applied voltage	3 – 9 V
Electrolyte dosage	0.5, 0.75, 1.0, and 1.5 g.
Agitation speed	100 – 400 rpm.
Electrode distance	2 cm, 3.5 cm, 5 cm.

3.4 Experimental Data Analysis

The percentage of methyl orange removed by the process was calculated using the following equation:

$$\% \text{ removal} = \frac{Ci - Cf}{Ci} \times 100 \quad \text{(Eq. 5)}$$

Where Ci= initial concentration of methyl orange

Cf= final concentration of methyl orange

To calculate the weight loss, electrodes were weighed before and after each experiment. The amount of electrodes that disintegrated during the E.C process was determined from this difference using the following formula:

$$M_{experimental} = M_{intial} - M_{final} \quad \text{(Eq. 6)}$$

$M_{initial}$ represents electrodes weight before experiment.

M_{final} is the final mass of the electrodes.

To calculate the effectiveness of electrodes, the following equation was used:

$$\text{Efficiency} = \frac{Mexperimental}{Mtheorical} \times 100\% \quad \text{(Eq.7)}$$

$$\text{The } M_{\text{theorical}} = \frac{M.I.t}{n.F} \quad \text{(Eq.8)}$$

Where, M= electrodes mass. Fe=55.85 g/mol, because steel is abundantly composed with iron, we also consider steel molar mass as 55.85 g/mol.

i= current

t=time

n=number of electrons transfer, 2 for iron

F=faraday constant (96486 C/mol).

3.4.1 Preparation of Calibration Curve

Based on the absorbance values obtained from the serially diluted methyl orange solutions, the calibration curve was created. In order to determine the final concentration of the methyl orange according to Eq. 5, the linear equation thus obtained is then applied.

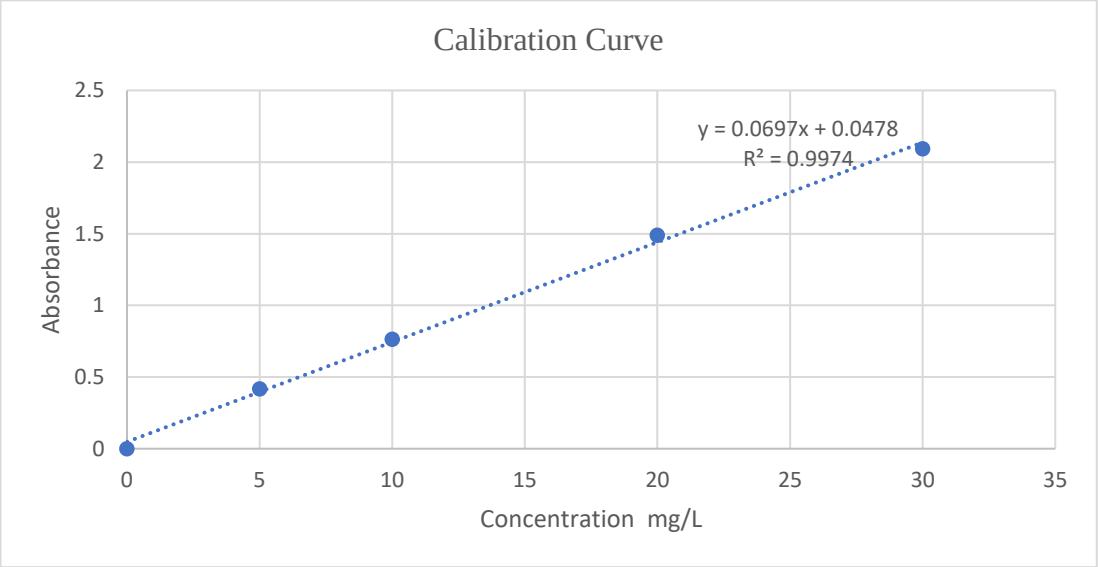

Figure 12: Calibration linear curve

3.4.2 Sludge Characterization

Filtered sludge from each experiment was dried in an oven at a temperature of 40 ^{o}C. The obtained powder was then examined using an FTIR (Fournier transform infrared spectrophotometer) after drying. The characterization results are helpful in identifying the types of metal hydroxide coagulants that were produced, and they may also shed light on how the pollutants bind to the coagulant to form the complex.

Chapter 4

RESULTS AND DISCUSSION

4.1 Effect of Operating Parameters

In order to optimise the water treatment process, the effects of the following factors were examined on the electrocoagulation process: pollutant concentration, pH, electrolyte, voltage, electrode distances, and speed of magnetic stirring.

4.1.1 Influence of pH

In the electrocoagulation process, the initial pH is a crucial factor. According to Kerwick et al. (2005), it is actually directly related to the hydroxide complexes that are created when the anode dissolves. In this study, it was discovered that pH 3 had the highest decolorization rate for both steel and iron electrodes.

The results using iron electrodes showed that the removal of dye was low at pH = 2 (39.40%), increased quickly to 98.23% at pH = 3, then decreased from pH = 5 (71.36%) to pH = 11 (48.59%) when other parameters remained constant (methyl orange concentration of 20 ppm, 2 cm of electrode distance, 200 rpm agitation speed, and 0.5 g electrolyte dose). At pH = 3, and pH = 5, 94.71% and 72.45% of the dye, respectively, were removed using steel electrodes under the same conditions. The removal percentage dropped from 75.77 to 48.95% between pH = 7 and pH = 11.

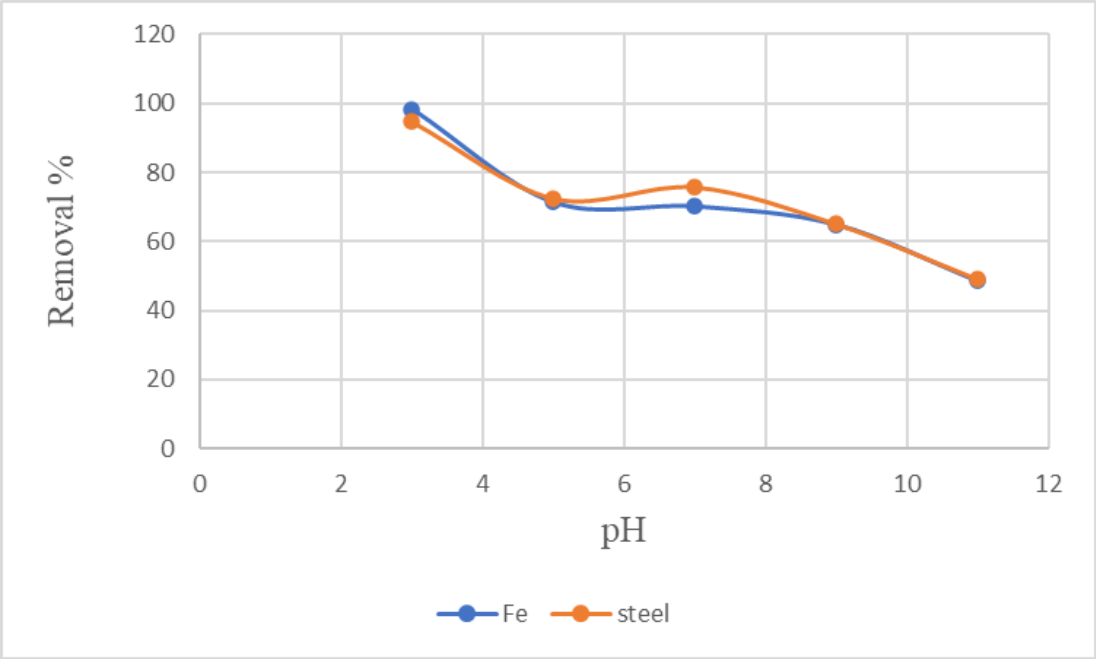

Figure 13:shows the impact of solution of pH on the removal of MO dye with Fe and steel electrodes. (Experimental conditions: 20ppm of MO, electrodes distance 2 cm, speed 200 rpm, electrolyte 0.5 g, reaction time 20 min, voltage = 6V)

When Sara et al. (2018) used iron electrodes to treat the methyl orange dye, they obtained the same optimum pH. The dye decolorization was approximately 96% after 12 minutes at pH = 3, according to the authors. According to Oladipo et al.2022, the presence of more insoluble $Fe(OH)_2$, which has a lower specific surface area, may be the cause of the E.C method's poor efficacy for the removal of methyl orange at pH 2. In reality, anode dissolution at a very acidic pH produces the Fe^{2+} ions in the E.C reactor. Due to the dissolved oxygen, these ions are oxidised to Fe^{3+} as the pH of the acidic solution rises, and H^+ ions become more prevalent and are reduced to hydrogen gas at the cathode.

As a result of their ability to electrostatically adsorb the anionic form of the methyl orange dye, soluble $Fe(OH)_3$ with a higher specific surface area and $Fe(OH)_2$ were both present at pH 3, and they were both capable of removing it with a very high removal efficiency. Beyond pH 6, Fe hydroxides begin to precipitate, and above pH 8,

the soluble anionic form of $Fe(OH)_4^-$ predominates (Duan and Gregory, 2003). This explains why at very high solution pH, a decreasing removal trend was seen.

4.1.2 Influence of Methyl Orange Concentration

When the electrocoagulation process is used to remove pollution in many experiments, the removal rate is directly correlated with the initial concentration. According to Nidal (2017), the removal of whey protein was 85, 55, and 50% for initial concentrations of 0.75, 1.5, and 3.0 g/L, respectively.

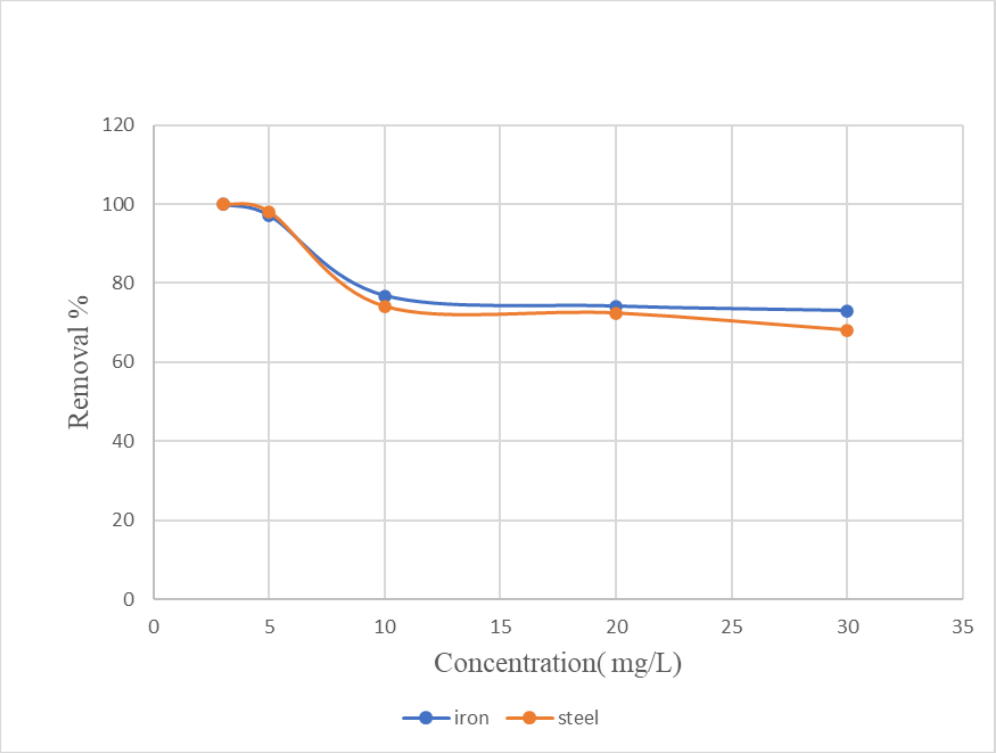

Figure 14:Effect of the initial concentration of MO on its removal efficiency (Experimental conditions: electrode distance of 2 cm, initial pH not adjusted, speed = 200rpm, electrolyte = 0.75g, time = 20 min, voltage = 6V)

The results of this study showed that using iron electrodes, the results were 100% for 3 ppm, 97.22% for 5 ppm, 76.80% for 10 ppm, 74.12% for 20 ppm, and 72.99% for 30 ppm, while using steel electrodes, the results were 100% for 3 ppm, 98.12% for 5 ppm, 74.15% for 10 ppm, 72.47 for 20 ppm, and 68.15% for 30 ppm.

The removal rate is higher when the initial concentration is lower because there is enough coagulant produced to coagulate the pollutant, but this rate drops as the pollutant amount rises.

4.1.3 Influence of Electrolyte

Theoretically, the increase in electrolyte concentration increases the rate of pollutant removal under constant voltage because electrolytes increase the conductivity of solution by facilitating ion mobility. Sara et al. (2018) compared how the removal of the methyl orange dye was affected by various electrolytes. The removal rates for $CaCl_2$, KCl, NaCl, Na_2SO_4, and $NaNO_3$ electrolytes were 94.7%, 86.8%, 82.3%, 77.9%, and 24.4%, respectively. The authors observed that the NaCl electrolyte required less energy than other electrolytes.

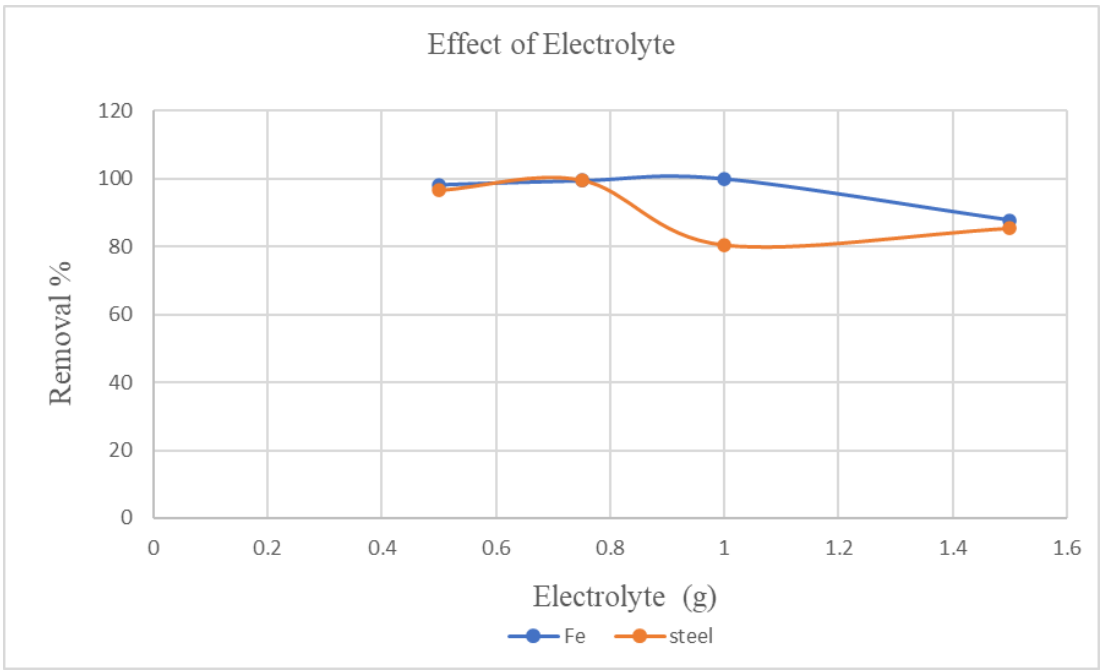

Figure 15: Effect of electrolyte dosage on the removal of MO dye (Experimental conditions: pH = 3, MO concentration = 20 ppm, electrode distance = 2cm, speed = 200rpm, voltage = 6V)

In this study, nearly no visible differences were observed when the electrolyte dosage was increased from 0.5 g to 1.0 g for both electrode types. While maintaining all other

parameters constant, removal rates of almost 100% were observed. Even though the cell voltage was kept constant, the removal rate dropped after 1.0 g, which may be due to a decrease in current density, which reduced the E.C system's capacity for direct removal. Subsequent experiments were conducted with 0.75 g of electrolyte.

4.1.4 Influence of Electrodes Distance

To determine the ideal electrode distance that produced the highest dye removal rate, various electrode distances were examined. The spacing between the electrodes has an impact on the ion's ability to diffuse after the reaction on the electrode. Due to the short circuit, which restricts metallic ion diffusion between the electrodes, the process becomes less effective when the distance between electrodes is very small (1 cm) (Zhang et al., 2022).

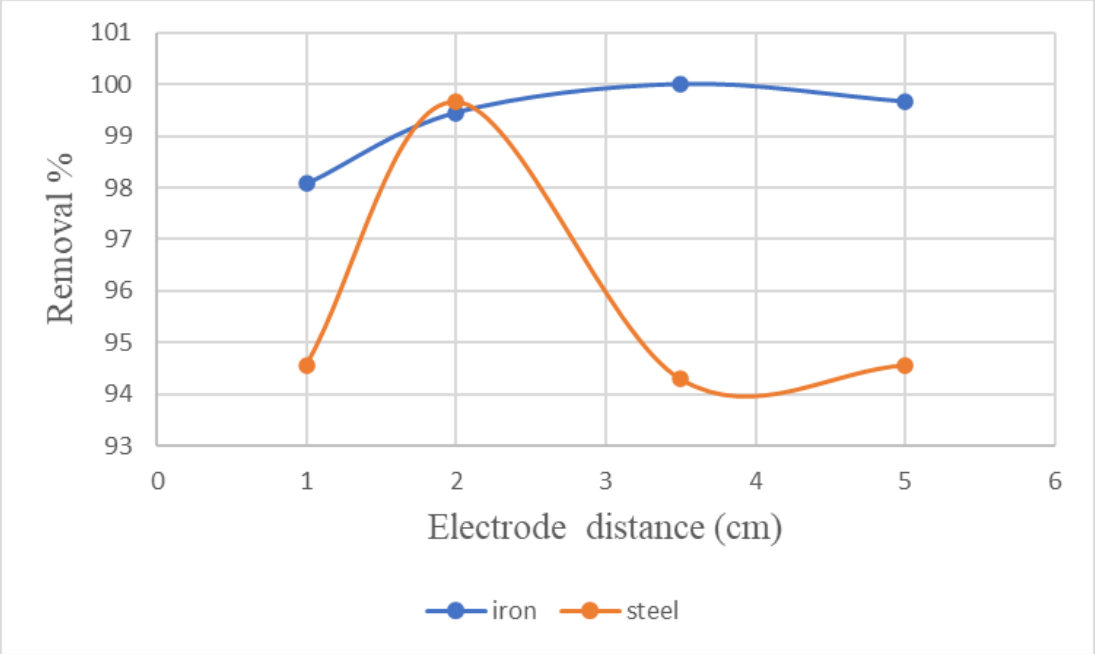

Figure 16: Effect of electrode distance on the removal of MO dye (Experimental conditions: pH= 3, MO cocentration = 20 ppm, electrolyte = 0.75 g, speed = 200rpm, voltage = 6 V)

But when the distance between the electrodes was raised to 2 cm, the resulting reduction in the reaction speed between the generated metallic ions provided the flocs

enough time to form, which was useful for removing a higher amount of the methyl orange species. A decreasing trend in MO removal was seen when the electrode distance was increased for the steel electrode beyond 2 cm, whereas no appreciable changes in MO removal were seen when the electrode distance was increased for the iron electrode to 5 cm. The findings indicate that, despite the lengthening of the route of travel, increasing the inter-electrode spacing between the steel electrodes has no direct impact on the transport of the generated metallic species towards the cathode.

4.1.5 Influence of Agitation

The medium is homogenised and prevented from forming a layer around the electrodes by agitating the reactor (Bayar et al., 2010). When the agitation speed is increased from 100 rpm to 200 rpm, as shown in figure 17, the dye removal efficiency increases. After that, a declining trend for dye removal was seen. The water hydrolysis reaction intensifies as the agitation speed increases. The water hydrolysis reaction creates OH^- ions, which are required to combine with iron cations to form an iron complex. The formation of sufficient coagulant to trap the pollutant species in the medium is inhibited or the dissolution of flocs by excessive speed above the optimal agitation speed is expected. As a result, 200 rpm was determined to be the ideal agitation speed for both electrodes.

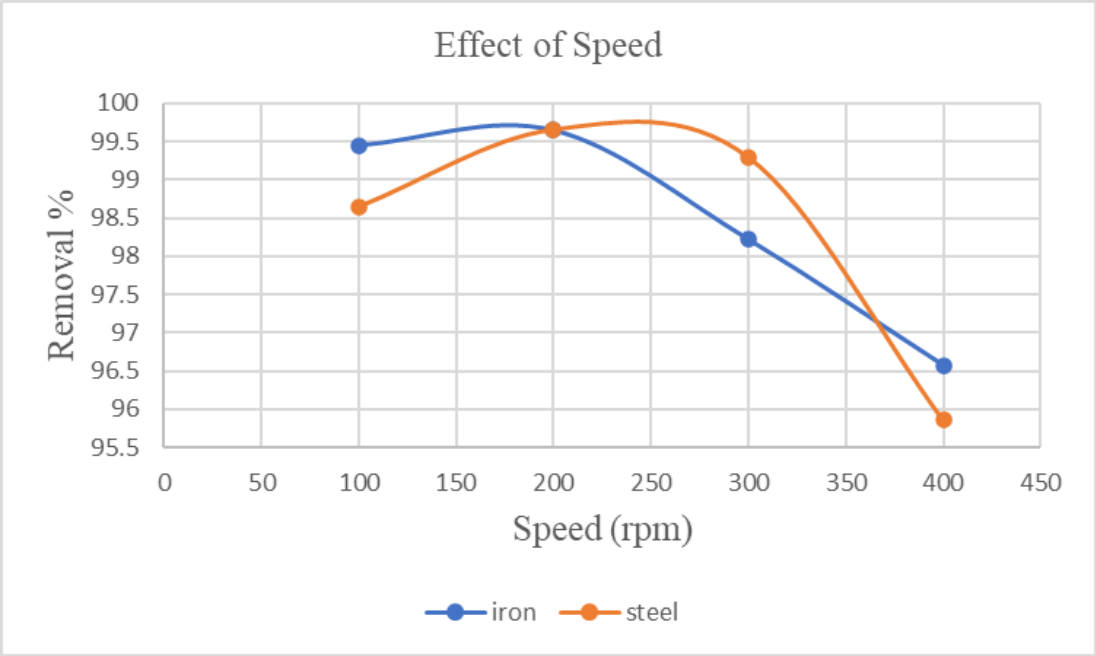

Figure 17: Effect of stirring speed on the removal of MO dye (Experimental conditions: pH = 3, MO concentration = 20 ppm, electrolyte = 0.75 g, voltage = 6 V, time = 20 min)

4.1.6 Influence of Voltage Variation

The rate at which an electrochemical reaction occurs in the cell is governed by the applied voltage, which is also a crucial factor (Mallah et al., 2001). In general, the rate of pollutant removal declines as applied voltage is raised. The removal of methyl orange increased significantly as the applied voltage for both electrodes was raised from 3 V to 6 V. The removal of methyl orange did not, however, significantly increase when the applied voltage was increased from 6 V to 9 V. Thus, methyl orange could be successfully removed using the 6 V applied voltage.

The results show that a sufficient amount of current was delivered to the solution at a voltage of 6 V, leading to a significant amount of M^{n+} ion generation. These ions improved the solution conductivity, which facilitated the current's flow (Syaichurrozi et al., 2020). However, the current density gradually increased at 9 V, producing a small amount of M^{n+} ions. Furthermore, the extremely high applied voltage might

result in unwanted side effects like parasitic reactions, which deplete the produced hydroxides (Lu et al., 2021).

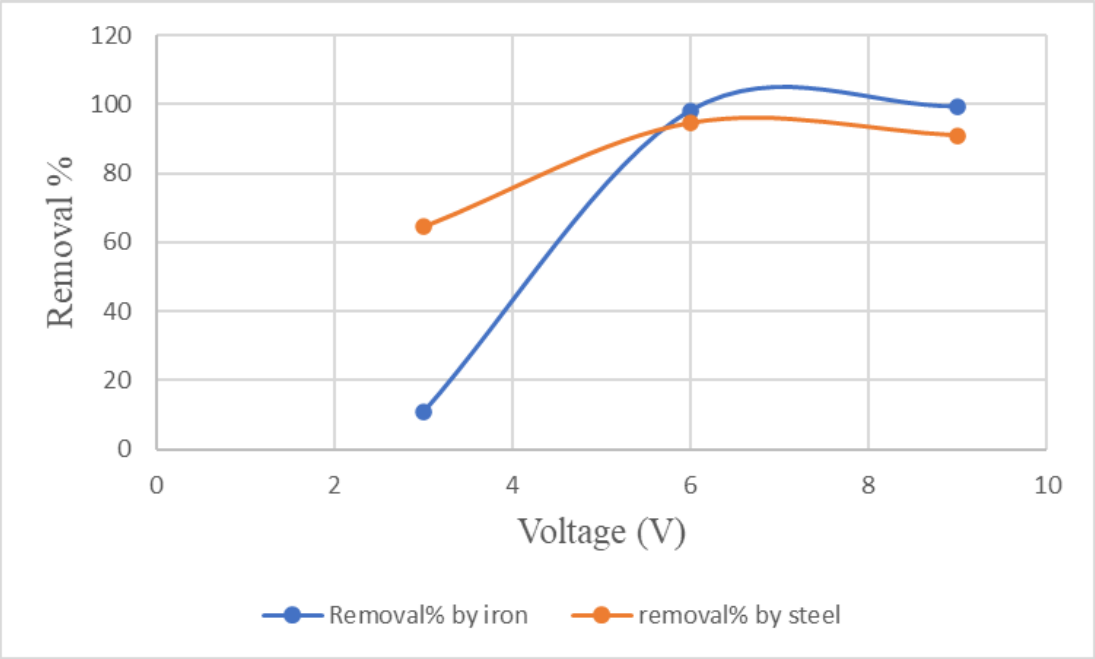

Figure 18: Effect of applied voltage on the removal of MO dye (Experimental conditions: pH = 3, concentration of MO = 20 ppm, electrode distance = 2cm, speed = 200rpm, electrolyte = 0.75g)

4.2 FTIR Analysis of Sludge Produced

Fourier-transform infrared spectroscopy was used to analyse the sludge that was collected following the treatment of methyl orange at various pHs (3,5,7,9, and 11). Figures 19 and 20 display the results of the characterization of the sludges produced by iron and steel electrodes.

All of the spectra contained peaks around 3200–3500 cm^{-1}, which denoted OH stretching from the metal hydroxides and N–H from the methyl orange azo group (Márquez et al., 2022). Methylene C-H's asymmetric stretching frequency is represented by the peaks at 2986 cm^{-1}.

Another peak can be seen around 2275-2200 cm^{-1}, which might be connected to the methyl orange's -CN vibration. Fe-O vibration may be responsible for a moderately broad band at about 650-586 (Oladipo et al., 2022).

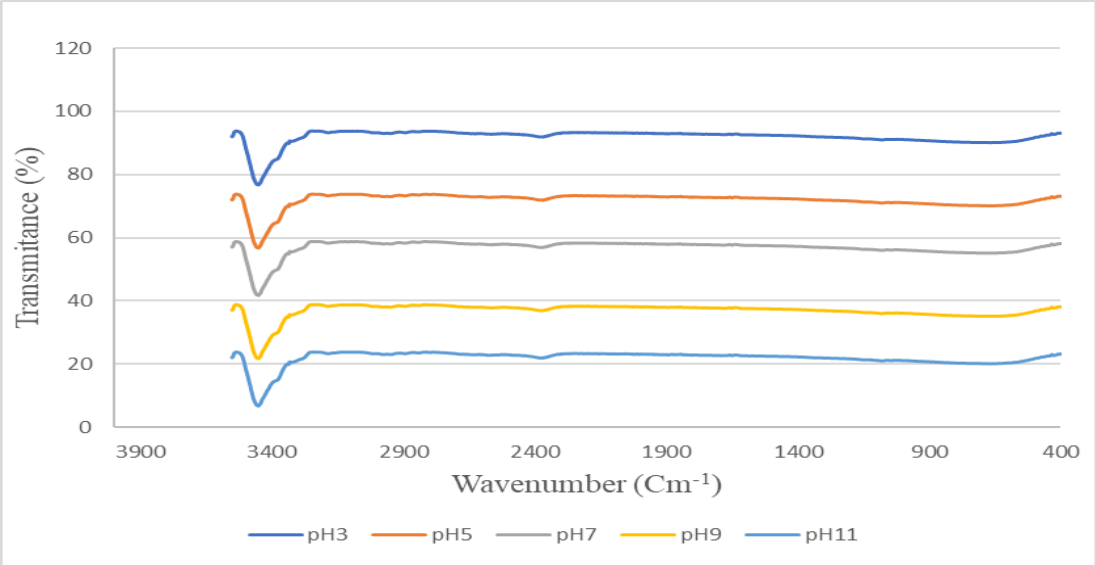

Figure 19: FTIR spectra of sludge from an iron electrode-methyl orange

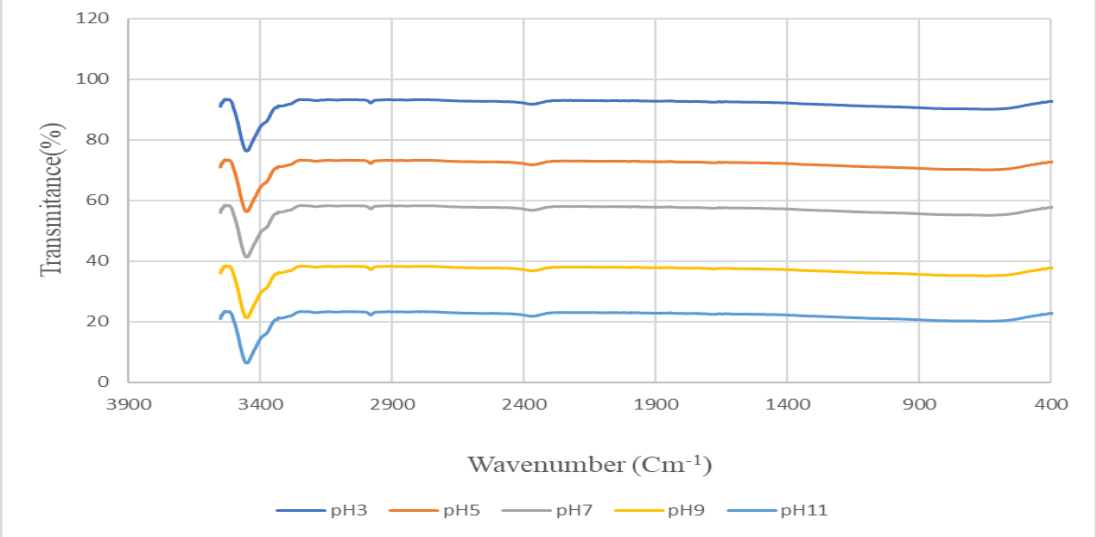

Figure 20: The FTIR spectra of sludge from a steel electrode- methyl orange

4.3 Estimated Cost for MO Removal by E.C Electrodes

The cost of dye removal includes the cost per unit of energy, the amount of energy used, the number of electrodes used, and the cost per unit of used metal. From Eq.4, the energy consumption of electrodes can be calculated as:

For iron electrodes Cen = $\frac{6\times0.15\times0.33}{0.0002}$ = 1.485 kwh/ m^3

For steel electrodes Cen = $\frac{6\times0.17\times0.33}{0.0002}$ = 1.683 kwh/ m^3.

On the basis of the findings from the pH effect, it is assumed that Fe3+ contributed more to the hydroxide formation, so Eq. 3 can be used to calculate the amount of Fe and steel electrodes used as follows:

For iron electrodes = $\frac{0.15\times1200\times55.845}{96485\times3}$ = 0.035 g

For steel electrodes: $\frac{0.17\times1200\times55.845}{96485\times3}$ = 0.039 g.

The price of 0.052548 kg of iron will be 0.07882 USD; keep in mind that 1 kg of iron costs 1.5 USD. Since 1 kg of steel costs 0.77 USD, the cost of 0.017837 was 0.01373 USD. The operating cost was calculated using prices from the TRNC in July 2021 ($0.28 per kWh of electricity and chemical costs, primarily consisting of electrolyte and pH adjustment: $0.035).

From Eq. 2, the operation cost can be calculated as:

For iron electrodes: Cop= $(0.28 \times 1.485) + (0.07882 \times 0.035) + 0.035 = 0.453$ USD$/$m^3$.

For steel electrodes: Cop= (0.28 × 1.683) + (0.01373 × 0.039) + 0.035 = 0.507 USD$/$m^3$.

From Eq.6, Mexperimental can be calculated (mass obtained from optimum conditions) as:

Fe electrodes $M_{experimental}$ = 51.319-51.284 = 0.035 g.

Steel electrodes $M_{experimental}$ = 17.2-17.153 = 0.047 g.

The electrode efficiency of the process is estimated according to Eq.7 as:

Iron electrodes: $\%=\frac{51.319-51.284}{0.05556}$ = 62.99%.

Steel electrodes: $\%= \frac{17.2-17.153}{0.05904}$ = 79.61%.

Chapter 5

CONCLUSION

In this study, iron and steel electrodes were used in an electrocoagulation procedure under a variety of reaction conditions to remove the methyl orange dye from a dye wastewater solution prepared in the lab. The sludge generated was collected and characterised by FTIR. Below are the summarised results and the observed trend:

- Using iron and steel electrodes, methyl orange dye removal efficiencies of 99.45% and 99.67%, respectively, were accomplished under the following circumstances: pH = 3, time = 20 min, electrolyte amount = 0.75 g of NaCl, voltage of 6 V, methyl orange concentration of 20 ppm and stirring speed of 200 rpm.
- The anionic form of the methyl orange dye and the predominant, high specific surface area $Fe(OH)_3$ and some $Fe(OH)_2$ electrostatically attracted to each other at pH 3, where the maximum removal was observed.
- For iron electrodes, the maximum dye removal was achieved at a distance of 2 cm, but steel electrodes continued to exhibit an increasing removal efficiency at distances greater than 2 cm.
- When the applied voltage was increased from 3 V to 6 V for both electrode types, the removal efficiency increased; however, a decreasing trend was seen at 9 V.

- The removal efficiency increased when the electrolyte dosage was increased from 0.5 g to 0.75 g, but no significant increases were observed above 0.75 g for either electrode.
- The efficiency of the steel electrode was 79.6%, compared to the iron electrode's 62.99%. It is important to note that treating 1 m^3 of methyl orange dye with an iron electrode costs 0.45 USD, whereas using a steel electrode costs 0.51 USD.
- Due to the presence of N-H and -CN groups from methyl orange and OH from the metal hydroxides, the sludge produced showed peaks around 3200-3500 cm^{-1} and 2275-2200 cm^{-1}. Additionally, the distinctive Fe-O peaks were seen, supporting the possibility that the methyl orange bonds were broken during the E.C procedure. More research is necessary to fully comprehend the removal mechanisms.

We conclude that electrocoagulation can be used as an alternative and cost-effective method to treat dye-polluted water and wastewater after taking into account the removal efficiency, process cost, and process time.

Future Work

The currently conducted research is laboratory-based due to time constraints and the lack of some materials. However, since background knowledge and experience have been acquired through the current thesis studies, future studies will incorporate studies using the actual textile effluent. Additionally, in the presence of pollutants from textile dyes, the ability of the electrocoagulation process to treat wastewater containing a variety of interfering pollutants will be examined. Additionally, the reactor tank will be enlarged to accommodate the electrocoagulation system in both batch and

continuous modes, with a pollutant capacity of at least 5 L. Additionally, both at the field and laboratory scales, the effects of electrode arrangement and geometry will be examined.

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