RESEARCH ARTICLE

Design of electrocoagulation system for removing non-sugar wastes from beet sugar press-water

Mohamed Saleh Sheta[1], Abd El-Motaleb M. Ramadan[2*], Mohamed M. Abd El-Wahab[3], Ibrahim Abd El-Ghany[1]

Abstract

Electrocoagulation (EC) cells, which work by passing an electric current through aqueous medium using electrodes, have proven to be a very effective technology for removing pollutants from wastewater.

The present study deals with the design of an electrochemical cell used to remove unwanted wastes from sugar beet press-water by electrocoagulation mechanism. The operational parameters controlling the removal efficiency of the target waste were studied.

These factors include pH, current density (CD), electrolysis time, stirring speed, surface area to volume ratio (S/V), electrode sets, electrode material type, and number of electrode plates. Wastes of sugar beet press-water to be removed are non-sugar materials, color and total hardness. The highest removal efficiencies achieved were 43.32%, 97.95% and 79.80% for non-sugar materials, color and total hardness, respectively.

The operating parameters that achieved these results were pH 10.7, current density 25.39 mA/cm^2, electrolysis time 60 min, stirring speed 350 rpm, 2Al-2Al electrode array, and S/V ratio 19.2 m^{-1}.

The experimental optimum values of anode mass loss and electrical power consumption were 0.76 kg/m^3 and 39 kWh/m^3, respectively.

Keywords: Beet Sugar Press-water, Color, Electrocoagulation, Sugar beet, Total hardness.

_____

[1] Science and Technology of the Sugar Industry Department, Faculty of Sugar and Integrated Industries Technology, Assiut University, 71525 Assiut, Egypt; Delta Sugar Company, Kafr El-Sheikh, Egypt

[2] Chemistry department, Faculty of Science, Kafr El-Sheikh University, Egypt

[3] Chemistry department, Faculty of Science, Assuit University, Egypt

[*]Corresponding author: Ramadanss@hotmail.com

Introduction

The sugar extraction industry from beet roots requires huge amounts of water, which prompted workers to look for a suitable way to treat it so that it could be reused again. Among these wastewaters is the press-water resulting from the pressure of beet pulp, during the stages of extracting sucrose from beet pulp, as shown in Figure 1.
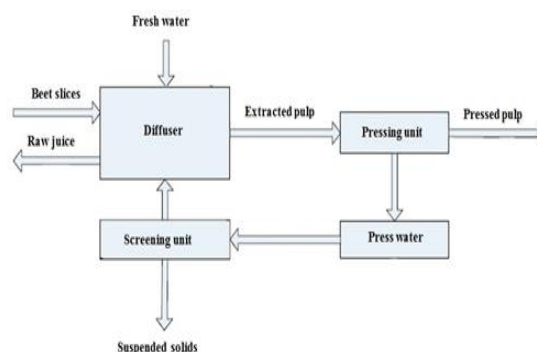

Figure 1. Sugar beet press water formation and its reuse in beet sugar extraction industry

In sugar beet root extraction plants, the press-water is usually returned to the diffuser and used like fresh water to extract sucrose from sugar beet slices. The reported analytical investigations of sugar beet press-water indicated that it is a dilute sugar solution containing solids ranging from 1 to 3 percent, of which sucrose is present at a rate ranging from 60 to 80 percent (Karathanos and Belessiotis 1999). This diluted sugar juice also contains inorganic salts of calcium, magnesium (responsible for water-hardness) sodium and potassium, colloidal compounds, and suspended solids (Karathanos and Belessiotis 1999). These impurities are present in a proportion ranging from 20 to 40% of the total solids and cause hindrance in the direct use of press water. Returning press-water to the diffuser with these characteristics will increase the impurity content in the raw juice.

The presence of these impurities affects the efficiency of the sugar extraction process, as it leads to decrease in the total production of sugar and its degree of purity (Bogliolo et al. 1997; Karathanos and Belessiotis, 1999; Noghabi et al. 2011). For example, the presence of sodium and potassium ions together increase the solubility of sucrose during the crystallization process to the extent that it hinders the crystallization step and thus increases the formation of molasses (Van der Poel et al., 1998).

In this regard, some reports related to the sugar industry stated that Na^+ and K^+ are the most important non-sugar species responsible for increasing molasses formation during the crystallization step (Van der Poel et al. 1998).

In light of this, it is imperative to treat press-water before reusing it to avoid the negative effects resulting from the presence of the aforementioned impurities. Purifying press water by the traditional filtration process does not allow the disposal of dissolved impurities.

In this context, the literature reported only one method for treating sugar beet press-water using reverse osmosis (RO) technology to obtain a stream of pure water for recycled use for sugar extraction.

In the same context, only a few attempts have been made to investigate the feasibility of using nanofiltration membrane processes in sugar beet press-water treatment (Nielsen et al. 1982; Gekas et al. 1985; Chu et al. 1988; Noghabi et al. 2011). The rarity of sugar beet press-water purification using membranes is mainly due to the viscosity of most sugar beet juices, the characteristics of which prevent satisfactory performance of membranes. Since the sugar beet press-water is returned directly to the diffuser, chemical or biological treatments are not suitable at all.

This is because the residual chemicals used can pass into the raw juice and contaminate it, and the same applies to biological treatment. Therefore, physical treatment is most suitable in the case of press-water treatment, and electrocoagulation is the most suitable technique because the removal mechanism includes coagulation, adsorption, sedimentation, and flotation. In this regard, electrocoagulation technology appears to be a promising treatment method due to its high efficiency, low maintenance costs, low labor requirement, fast results, short operating time, no or minimal chemicals, stable performance and minimal sludge production (Mollah et al. 2004). Moreover, EC technology requires a smaller design space compared to other treatment methods. In addition, pH control may only be necessary in the event of extreme values. Due to the above mentioned advantages of electrocoagulation technology, as well as its versatility and environmental compatibility, it has received a great deal of attention in the treatment of various wastewaters as well as the safe disposal of various pollutants (Ahmadzadeh et al. 2017; Garcia-

Segura et al. 2017; Sahu, 2019; Gondudey and Chaudhari, 2020; Sharma and Simsek, 2020; Bhagawati et al. 2022; Das et al. 2022; Mahroudi et al. 2022; Patel et al. 2022; Abdul Rahman et al. 2023; Dolatabadi et al. 2023; Mao et al. 2023; Medina-Collana et al. 2023; Rumky et al. 2023; Yaqub et al. 2023; Fadhila et al. 2024).

According to the literature search, there are no previous studies on treating sugar beet press-water by electrocoagulation technology. Accordingly, any work that deals with studying the use of electrocoagulation technology in the treatment of sugar beet press-water is a novel scientific addition in the field of wastewater treatment.

The treatment of sugar beet press-water allows its reuse, recovery of the sugar content and protection of the environment from pollutants, and is therefore considered a green treatment process. The present study aims to design an EC system for treating sugar beet press-water for Delta Sugar Company in the Arab Republic of Egypt.

Since the most commonly used electrode materials in electrocoagulation cells are aluminum and iron because they are readily available, cheap and highly effective, they were used in the present study (Kobya et al. 2003; Ilhan et al. 2008; Ozyonar and Karagozoglu, 2011; Igwegbe et al. 2021).

The effect of operating parameters such as current density, pH, stirring speed, electrode material type, number of electrode plates used, electrolysis time and surface area to volume ratio (S/V ratio) on the treatment efficiency will also be studied. It is worth noting here that the novelty of the present work is the treatment of sugar beet press-water using electrocoagulation technology for the first time.

Materials and Methods

The chemicals used in the present study are of high purity and were purchased from reputable companies such as Aldrich and Merck. The chemicals and reagents used in the current study include ammonia buffer of pH 10, ammonium hydroxide, ammonium chloride, lead acetate, ethylene diamine tetra acetic acid disodium salt, Eriochrome Black T indicator, and bi-distilled water.

The sugar beet press-water under study was obtained from the wastewater of the wet pulp pressing unit of Delta Sugar Company in Egypt.

The studied samples were transported to the laboratory using an insulated ice box and then stored at a temperature below 4 ℃ to avoid any biological degradation or contamination before performing the respective electrocoagulation experiments. The present study continued for two consecutive seasons in 2022 and 2023, during which press-water samples were taken to conduct the current study.

2

Equipments

The experimental procedures of the current study were conducted using the following tools and equipments: the electrocoagulation unit parts include two plates of aluminum (anode) and two plates of iron (cathode); Pyrex glass beaker of 2.5 liter, converter of AC to DC switcher power supply 800W [KIT.SMPS. 60V- 13A] with digital power supply [DPS50V15A] LCD and cables, Hot plate magnetic stirrer of Stuart model UC152, digital pH meter Jen way 3510 (Metrohm), MCP sucrometer 5300, Anton par, Hach DR2500 spectrophotometer, and Refractometer RX-5000 (ATAGO Co., LTD).

Electrocoagulation cell construction

The anode and cathode of the present electrocoagulation system consists of two plates of aluminum and two plates of iron respectively which are placed in a Pyrex glass beaker of 2.5 litres (Figure 2). The electrodes used are $8 \times 0.2 \times 16$ cm (25.6 cm3) connected to an AC to DC converter and the distance between anode and cathode is 1 cm. The immersed length of the electrodes is 8 cm, in a volume of the tested sugar beet press-water sample of 2 liters. The glass vessel containing the components of the electrocoagulation cell was placed on the surface of hot plate with a magnetic stirrer to provide the necessary stirring throughout the duration of the experiments.
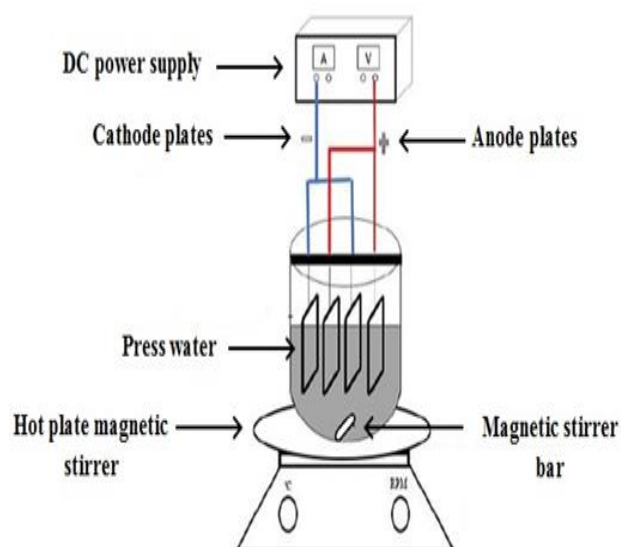

Figure 2. The vertical flow plate electrocoagulation system

Electrocoagulation experiment

The press-water sample under study was taken in a volume of 2 liters directly from the working tank and filtered through a 90 mesh sieve to remove any fine particles. The purity of the sample was verified by performing polarization and brix tests using specialized equipments.

This water sample was then transferred to the glass beaker of the electrocoagulation cell as shown in Figure 2. The water samples taken for analytical tests were returned to their places in the EC cell and the running experiments were repeated three times at electrical current values of 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15 amperes (A) for 60 minutes.

Analytical techniques

During the EC experiments, samples of the press-water were taken before and after each operation and analyzed to estimate the percentage of non-sugar materials, color, and total hardness. All analysis operations performed are described as shown in the following sections:

Determination of non-sugar removal efficiency

The total soluble solids (TSS) and apparent sucrose content of sugar beet press-water was determined by refractometer technique. In this context, TSS in water sample was determined by using a fully automatic digital refractometer, model RX-5000 (ATAGO Co., LTD) according to Delta sugar company procedures. The results obtained are expressed as Refractometric Dry Substance (RDS) or Brix. RDS or Brix is the total concentration of both non sugar (NS) substance and sucrose (S). The apparent sucrose content of beet sugar is determined by polarimetric method. In this regard, a 50 ml sample of sugar beet press-water was taken and placed in a 200 ml volumetric flask, and the volume was completed to 200 ml with distilled water. A few drops of lead acetate reagent (35 %) is added to this solution, and then this mixture is shaken well and filtered. Finally, the filtrate is taken and measured on the automatic saccharimeter device to determine the concentration of sucrose.

The sucrose percentage is determined from the relation:

$$\text{Scurose \%} = \frac{\text{Sucrose content}}{\text{Brix}} \times 100$$

The non sugar percentage then determined from the relation:

$$\text{NS \%} = 100 - \left(\frac{\text{Sucrose content}}{\text{Brix}} \times 100 \right)$$

The non sugar removal efficiency (NSRE) percentage of the investigated sugar beet press-water sample was determined from the following relationship:

$$\text{NSRE\%} = \frac{[\% \text{ NS}]_b - [\% \text{ NS}]_a}{[\% \text{ NS}]_b} \times 100$$

where [NS]b and [NS]a are the non sugar concentration of press-water samples before and after treatment process respectively.

CRE% determination:

Determination of color removal efficiency (CRE) of the investigated sugar beet press-water sample was achieved by measuring the absorbance (A) at 450 nm of 5 ml press-water sample before and after treatment process respectively. The color depth of the press-water sample was determined according to the International Commission for Uniform Method of Sugar Analysis (ICUMSA) from the relationship:

$$\text{Color depth (C)} = \frac{A \times 10^5}{\text{Brix} \times 5} \quad \text{(ICUMSA)}$$

where A the absorbance measured for a 5 ml sample of press-water. The obtained results are given in Table 2.1:

Color removal efficiency (CRE) percentage was calculated from the following relation:

$$\text{CRE\%} = \frac{C_b - C_a}{C_b} \times 100$$

where Cb and Ca are the color depth in ICUMSA unites of press-water samples before and after treatment process respectively (see Table 2.).

THRE% determination

The total hardness of the sugar beet press-water sample was determined according to the protocol of Delta Sugar Company, recommended by Braunschweigische Maschinenbauastalt GmbH (B.M.A manual). In this regard, 50 ml of press-water sample and 10 ml of ammonia buffer (pH = 10) was titrated against disodium salt of ethylene diamine tetra acetic acid (Na2EDTA) (0.1 M) solution in presence of Eriochrome black T as metal indicator at room temperature.

The total hardness (TH) of the press-water sample was determined in mg/L of calcium oxide from the following relationship, knowing that the molecular mass of calcium oxide is 56:

$$TH = \frac{M_{EDTA} \times V_{EDTA} \times 56 \times 1000}{V_{press\ water\ sample}} \quad \text{mg/L CaO}$$

The total hardness removal efficiency (THRE) percentage was determined from the relationship:

$$\text{THRE \%} = \frac{TH_b - TH_a}{TH_b} \times 100$$

where THb and THa are the total hardness expressed as mg/L CaO of press-water samples before and after treatment process respectively (see Table 2).

Determination of pH versus applied current intensity

Table 1. shows the results of measuring the change in pH versus the applied electric current during the ongoing EC experiments

Table 1. The changes in pH against the applied electrical current

Ampere (A)	pH Before	pH After
3	4.5	7.6
5	4.5	7.8
6	4.5	8.2
7	4.5	8.7
8	4.5	9.2
9	4.5	9.5
10	4.5	9.8
11	4.5	10.1
12	4.5	10.4
13	4.5	10.7
14	4.5	9.7
15	4.5	9.6

Determination of removal efficiency versus applied current intensity

Preliminary EC experiments were conducted on the sugar beet press-water to determine the best treatment range of applied current (ampere) to successfully remove of non-sugar, color and total hardness and the obtained results are given in Table 2. The current EC experiments were repeated three times for each value of the applied current before and after the EC operations and the average results are taken and listed in Table 2.. It is also worth noting that all EC experiments were performed at room temperature.

Table 2. Values of Non-sugar%, Sucrose%, color and total hardness percentages before and after the electrocoagulation process.

Ampere	Non-sugar% Befor	Non-sugar% After	Sucrose % Befor	Sucrose % After	Color (ICUMSA) Befor	Color (ICUMSA) After	Total hardness (mg/L) Before	Total hardness (mg/L) After
3	28.5	27.50	71.5	72.5	7100	1702	650	386
5	28.5	27.39	71.5	72.61	7100	452	650	338
6	28.5	25.77	71.5	74.23	7100	429	650	304
7	28.5	23.73	71.5	76.27	7100	361	650	299
8	28.5	22.95	71.5	77.05	7100	252	650	293
9	28.5	22.00	71.5	78.00	7100	226	650	260
10	28.5	21.83	71.5	78.17	7100	222	650	252
11	28.5	21.92	71.5	78.08	7100	177	650	229
12	28.5	21.19	71.5	78.81	7100	171	650	192
13	28.5	17.24	71.5	82.76	7100	159	650	150
14	28.5	20.27	71.5	79.73	7100	162	650	228
15	28.5	20.36	71.5	79.64	7100	164	650	250

Results and discussion

Sugar beet press-water (SBPW) is produced in one of the stages of sugar extraction from beet pulp (Figure 1), where it contains an un-extracted percentage of sucrose in addition to a percentage of non-sugar (NS) materials. In other words, sugar beet press-water is one of the main wastewaters in the sugar industry, which is currently returned to the diffuser without any further treatment. The non-sugar residuals in press-water can deposit on the internal surfaces of evaporators, thus reducing their efficiency and consuming more energy.

4

Also, the presence of non-sugar pollutants will negatively affect the efficiency of the crystallization process and the quality of the final sugar produced. Thus, removing non-sugar contaminants would reduce the cost of cleaning the internal surfaces of evaporators, where the juice is present immediately before the crystallization process. Treatment of press-water will reduce the load on the juice treatment unit and then increase its efficiency and this leads to increase the sugar yield.
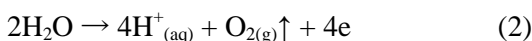
The present study aims to treat sugar beet press-water by removing organic and inorganic wastes, which include non-sugar components, hardness and color. To achieve this goal, a new electrocoagulation (EC) system was designed and described in the experimental section. In this regard, the present electrocoagulation study mainly focuses on the treatment of sugar beet press-water using Al and Fe electrodes.

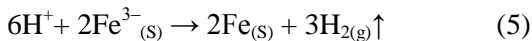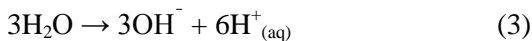**Theory of the present electrochemical coagulation processes**

The anode of the current electrocoagulation unit is aluminum plate while the cathode is made of iron and both are externally connected to a power unit (AC to DC converter) as shown in Figure 2. The anode was chosen from aluminum because of its good properties that suit the current working conditions. This is evident from the fact that the flocs resulting from the aluminum electrode by electrolysis processes are characterized by a strong adsorption capacity, which is the key factor in removing various pollutants (Liu et al. 2022).

Under the prevailing experimental conditions of the present study, the cathodic and anodic electrochemical reactions occurring during the press-water treatment process can be summarized as follows:

Anodic reaction (oxidation):

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e \qquad (1)$$

$$2H_2O \rightarrow 4H^+_{(aq)} + O_{2(g)}\uparrow + 4e \qquad (2)$$

Cathodic reaction (reduction):

$$3H_2O \rightarrow 3OH^- + 6H^+_{(aq)} \qquad (3)$$

$$Fe_{(S)} + 3e \rightarrow Fe^{3-}_{(S)} \qquad (4)$$

$$6H^+ + 2Fe^{3-}_{(S)} \rightarrow 2Fe_{(S)} + 3H_{2(g)}\uparrow \qquad (5)$$

Each dissolved hydrogen ion formed in equations (2) and (3) gains an electron from the cathode and becomes a hydrogen atom that combines with another hydrogen atom to form a molecule of hydrogen gas.

In the bulk of solution, the trivalent aluminum ion formed combines with hydroxide ion to form $Al(OH)_3$ as shown in equation 6.

$$Al^{3+}_{(aq)} + 3OH^-_{(aq)} \rightarrow Al(OH)_{3(aq)} \qquad (6)$$
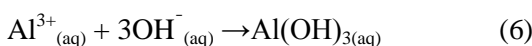
The formed aluminum hydroxide, $Al(OH)_3$, acts as a cushion (substrate) on the surface of which most of unwanted materials are removed physically by adsorption. This scenario is expected to occur due to the large surface area of the colloidal particles of $Al(OH)_3$ which form physical bonds with various pollutants and form flocs or agglomerates. On the other hand, H_2 and O_2 gases have been demonstrated to be produced as by-products of various secondary reactions in EC cells (Sahu et al. 2014; Moussa et al. 2017; Abbas and Ali, 2018; Ingelsson et al. 2020; Kim et al. 2020). In this regard, the presence of H2 gas is necessary to keep the flocs buoyant and prevent them from sinking to the bottom due to gravity (Kobya et al. 2020).

The evolved hydrogen gas raises the flocs to the surface of the solution, a process called electro-flotation, and the flocs can be removed by scraping. In the same context, the O_2 forms reactive oxygen species (ROS) such as H_2O_2, $HO^{\bullet}$, $O_2^{\bullet-}$ … etc, which helps in the oxidation of many toxic and non-toxic pollutants (Nidheesh and Singh, 2017). The formed highly heavy flocs sink to the bottom and form sludge (Figure 3.), which can be efficiently, removed using various methods.
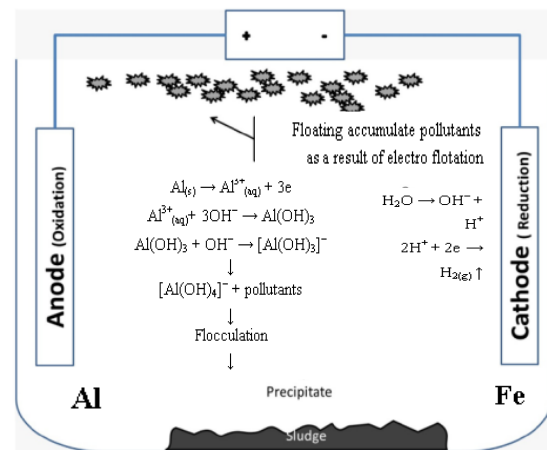

Figure 3. Diagram describing the current electrocoagulation cell.

When an electrical current passes through the electrolytic cell, the aluminum anode undergoes oxidation, and Al^{3+} ions in the solution dissociate, releasing three electrons for each Al^{3+} ion (Zaied et al. 2020). The number of dissociated Al^{3+} ions is determined based on the formula of Faraday's law as shown in relation (8) (Singh and Ramesh, 2014):

$$m = \frac{ITM_w}{ZF} \qquad (8)$$

Where, m = mass of anode dissolved, I = current, T = time of operation, Mw = molecular weight of aluminum metal, F = Faraday's constant (96,485C/mol), Z = number of electrons involved in the reaction (Singh and Ramesh, 2014).

This explanation may illustrate the mechanism of the current electrochemical coagulation process for treating sugar beet press-water.

Operating parameters controlling the NSRE, CRE and THRE

A literature survey indicates that the removal efficiency of sugar beet press-water contaminants such as non-sugar residuals, color and total hardness by electrocoagulation (EC) technology is controlled by a set of operating parameters (Kabdaşlı et al. 2012; Manjunath et al. 2023).

The operating parameters in question include current density, stirring speed, electrode type, number of electrodes used, electrolysis time, and surface area to volume ratio (S/V ratio). To evaluate the efficiency of the current treatment EC system in treating sugar-beet press water, the effect of the above mentioned operating parameters will be studied.

For the present experiments, sugar-beet press water samples were taken before and after EC treatment when NSRE, CRE, and THRE were determined. After each use of electrodes in ongoing EC operations, the electrodes are washed, dried and the experimental mass change of both electrodes is determined. Halfway through the EC treatment time, the resulting lighter flocs were observed to float to the surface as shown in Figure 3. In the same context, after the EC treatment time was over, it was observed that the heavier flocs (sludge particles) sank and settled at the bottom of the tank due to gravity as shown in Figure 3. After gravity sedimentation of heavy flocs, the remaining pure treated water in the tank was tested to estimate the removal efficiency of the studied pollutants.

Effect of pH

Among the most important parameters controls the performance of EC cell is pH of pres-water under investigation (Gürses et al. 2002; Adhoum and Monser, 2004; Kumar et al. 2004; TolgaYılmaz et al. 2018).

The pH change during the electrocoagulation experiment can affect the stability and type of aluminum hydroxide formed. In this regard, the electrolytic soluble Al^{3+} can form different types of aluminum hydroxide based on the pH value of the environment.

The effect of pH on the studied Al-Fe composition pattern was studied and the results in Table 1. showed a gradual increase in the pH range from 4.5 to 10.7 for press-water with increasing applied electric current (3-15 A). These results are consistent with those reported in a similar treatment of sugar industry wastewater by an EC cell using an aluminum anode and an iron cathode (TolgaYılmaz et al. 2018). The observed gradual rise in pH value is due to the fact that as the current intensity increases, the electron density also increases, which increases the rate of hydrolytic reduction of water

adjacent to the cathode. This in turn increases the rate of OH^- production and thus the pH of the press-water sample increases from 4.5 to 10.7. For the present pH range in an aqueous medium, several types of monomeric aluminum hydroxide species can be formed which may include $Al(OH)^{2+}$, $Al(OH)^{2+}$, $Al(OH)_3$, and $[Al(OH)_4]^-$ (Gürses et al. 2002; Chen, 2004; TolgaYılmaz et al. 2018). In addition several polymeric hydrolysis products can be produce such as $Al_6(OH)_{15}^{3+}$, $Al1_3(OH)_{24}^{7+}$, $Al_7(OH)_{17}^{4+}$ and more (Gürses et al. 2002; Chen, 2004; Kumar et al. 2004; TolgaYılmaz et al., 2018). This diversity of aluminum hydroxide species produce by electrolysis provides a good opportunity for adsorption of many oppositely charged particles or ions such heavy metal, sodium and potassium ions.

Overall, the maximum removal efficiency for non-sugar materials, color and total hardness was achieved at a pH value of 10.7 which corresponds to a current intensity of 13 A and current density of 25.39 mA/ cm^2

Effect of current density (CD mA/ cm^2)

The current per unit surface area of the electrode of an electrolytic cell is called the current density (CD) which controls the amount of metal ions released into the medium during the electrolysis process (Eyvaz et al. 2009). Current density is a very important operational parameter in the performance of an EC water treatment system because it determines the rates of both coagulant dosage, and bubble formation in addition to size, and flocs growth which in turn affects the efficiency of the water treatment operation (Naje et al. 2017).

The electrical current density (CD) was calculated from the relation: CD = I/S; where, I is the current intensity (mA) passing through the solution and S is the area of electrode (cm^2) (Nandi and Patel 2017).

Non-sugar removal efficiency (NSRE)

In the present EC system, and in the case of Al-Fe electrodes combination, $Al(OH)_3$ is the electrochemically released coagulation species under the influence of an electric current ranging from 3 to 15 ampere giving current densities ranging from 5.86 to 29.29 mA/cm^2 (Table 3).

In the same regard, the S/V ratio was 12.8 m^{-1} and the system was subjected to stirring and the running experiments were repeated three times for each value of the applied current density and the average results obtained are recorded in Table 3.

The data in Table 3. show that except for the current density values of 27.34 and 29.29 mA/cm^2, the NSRE increases with increasing current density in accordance with Faraday's law (the higher the current, the higher the current density) (Sahu et al. 2014). This finding is consistent with the fact that the release rate of Al(III) ions increases with increasing applied current density (Badakhshan et al. 2019; Sharma et al. 2020).

6

At this stage the amount of electrochemically generated $Al(OH)_3$ flocs increases and as a result the NSRE increases. As shown in Table 3. the highest NSRE value of 39.54 was achieved at a current density value of 25.39 mA/cm^2.

This result is comparable to a study that reported that an applied current density of 25 mA/cm^2 was sufficient to achieve 98.5% COD, 98% turbidity, 92% total organic carbon (TOC), and 100% color removal efficiency from peat water (Abdul Rahman et al. 2020). A similar study indicated that applying a current density of 25 mA/cm^2 achieved removal efficiencies of 84, 81, 93 and 97% for total nitrogen, total suspended solids, chemical oxygen demand and biological oxygen demand, respectively (Ahmadian et al. 2012). On the other hand, increasing the electron density above 25.39 mA/cm^2 led to a decrease in the removal efficiency, as shown in Table 3.

This behavior can be explained on the basis that increasing the electrolysis current resulted in the production of excess Al^{3+} (Badakhshan et al. 2019; Sharma et al. 2020), which reversed the colloidal surface charge, formed colloidal repulsion, destroyed the agglomeration (flocs), reduced the agglomeration ability, and thus reduce the NSRE %, and THRE % of sugar beet press-water (Fouladgar and Ahmadzadeh, 2016).

Moreover, the size of the electrolytic bubble decreases with increasing current density, and the small nuclear bubbles merge, resulting in the creation of coarse bubbles.

The combination of these two effects leads to a reduction in the treatment efficiency as a result of the applied current density exceeding a certain limit. Therefore, the optimum current density produces the finest bubbles, and this depends on the value of the applied current, which also affects the energy consumption and the processing system (Mohtashami and Shang, 2019). In the same regard, the occurrence of electrodes passivation cannot be excluded, which has a negative effect on the removal efficiency at values higher than the recorded ideal current density value of 25.39 mA/cm^2. This explanation finds support from the results and interpretations of a number of similar previous studies (Garg and Prasad, 2016; Abdel-Shafy et al. 2020). Therefore, current density is a critical parameter in the EC process which must be optimized to achieve the desired processing performance.

Color removal efficiency (CRE)

The color of sugar crystals is a measure of its quality, the less color the higher the quality. In this context, sugar extraction companies are keen to produce a product that is almost colorless. Since sugar beet press-water is reused in extracting sugar from beet roots, it is very important to remove any color in that water before

reusing it. In the frame of the present study the color removal efficiency (CRE) was determined and correlated with current density and pH of press-water as shown in the data tabulated in Table 3.

The data in Table 3. indicate that, at an initial pH of 7.6 and a current density 5.86 mA/cm^2, the color removing increased to 76.02% after 60 minutes.

In the same context, at a pH of 8.2, a current density of 15.63 mA/cm^2, and a time period of 60 minutes, the CRE reached a relatively high value of 96.45%. Above these values of pH and current density and under the same operating conditions, the decolorization efficiency increased insignificantly as shown in Table 3. Based on these results, it can be concluded that pH and current density control the amount and type of aluminum hydroxide formed in an EC cell consisting of the 2Al-2Fe composition pattern.

The present results indicate that the type and amount of coagulants generated in the EC cell at pH 8.2 and current density of 15.63 mA/cm^2 are suitable and sufficient to significantly remove colored materials in the investigated press-water samples. Thus the pH 8.2 and current density 15.63 mA/cm^2 are the optimized operating parameters for the decolorization efficiency of press-water under investigation. However, the color removal efficiency results in the present study are comparable to those reported using EC technology (Demirci et al. 2015; Pirkarami and Olya, 2017).
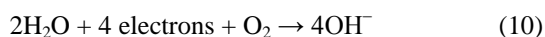
Total hardness removal efficiency (THRE)

Hard water is water that contains high concentrations of both Ca(II) and Mg(II) ions and water hardness is divided into two types, permanent and temporary, depending on the acidic radical incorporated in the binary salt (MX1 or 2). For temporary hardness X is bicarbonate (HCO_3^-) radical while for permanent hardness X is chloride or sulfate anions.

Hard water causes major problems and difficulties in most industrial processes that use large and intensive quantities of water, such as in the sugar extraction industry from beet roots. EC technology has shown high efficiency in removing many contaminants from water, including permanent and temporary hardness (Pooja and Salkar, 2017; Wang et al. 2021; Medina-Collana et al.2022).

Electrochemical principle of hardness removal

The electrolytic hardness removing relies on creating a high pH medium around the cathode by water-oxygen reduction reactions that release OH^- ions through the cathodic reactions (Eq 9, 10) (Hasson et al. 2011):

$$2H_2O + 2 \text{ electrons} \rightarrow 2OH^- + H_2\uparrow \qquad (9)$$

$$2H_2O + 4 \text{ electrons} + O_2 \rightarrow 4OH^- \qquad (10)$$

As shown in Table 1. the pH values gradually increase with increasing applied electrical current to reach 10.7. In an aqueous medium with pH > 10, the HCO^{3-} (Eq. 11) ion is converted to CO_3^{2-}, which combines with the Ca(II) ion to form a precipitate of $CaCO_3$ (Eq. 12) and deposits on the surface of the cathode (Zhi and Zhang, 2014).

$$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O \qquad (11)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\downarrow \qquad (12)$$
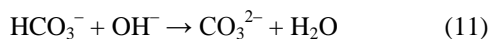
In the same regard, this alkaline environment promotes the precipitation of Mg(II) ions in the form of $Mg(OH)^2$ (Eq 13) which sinks to the bottom of the EC cell vessel and settles on the surface of sludge (Kalash et al.2015).

$$Mg^{2+} + OH^- \rightarrow Mg(OH)_2\downarrow \qquad (13)$$
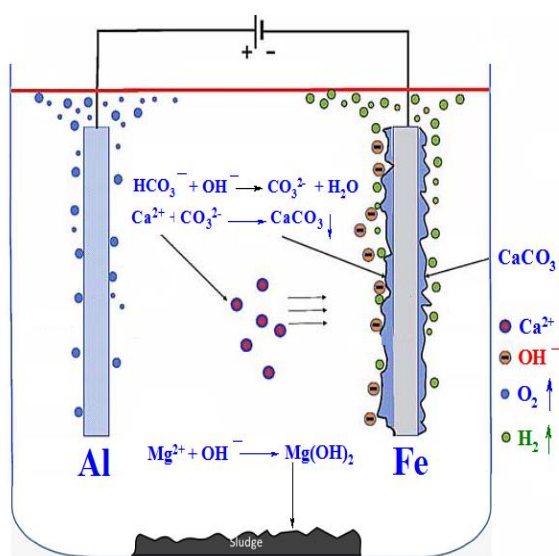

Figure 4. Summary of the chemical reactions that occur during the removal of water hardness by an EC cell

As shown in Table 3. there is a correlation between increasing both electron density and pH and increasing the percentage of hardness removal in press-water samples. For a period of time of 60 minutes and at an initial pH of 7.6 and a current density 5.86 mA/cm^2, the removal efficiency of hardness was 40.62 %. As the current density continued to increase to 25.39 mA/cm^2 and the pH value increased to 10.7, the hardness removal efficiency increased to its highest value of 76.92.

As the current density applied to the electrocoagulation cell increases from 5.86 to 25.39 mA/cm^2, the number of Al^{3+} ions released increases and the number of hydroxide flocs formed also increases; the final result is increased the efficiency of hardness removal. However, the present results indicate excellent removal efficiency compared to recently published results of a removal efficiency of 25.83% at a CD value 22.4 mA/cm^2 (Medina-Collana et al. 2023).

In the same context, the data in Table 3. show that above the optimum CD value of 25.39 mA/cm^2, the hardness removal efficiency drops to 61.60% (Table 3).

This result can be attributed to a decrease in cathode activity due to the formation of a permanent layer of $CaCO_3$ on the cathode surface.

Figure 4. shows a summary of the chemical reactions that occur during hardness removing by EC method and shows the deposition of a layer of calcium carbonate on the surface of the cathode.

This interpretation is supported by the experimentally measured increase in cathode mass after the end of the total hardness removal experiment.

Table 3. Effect of electrical current density on NSRE %, CRE % and THRE % of sugar-beet press water in the case of 2Al-2Fe electrode combination for a period of time 60 minutes at room temperature, S/V ratio 12.8 m^{-1}, the stirring speed 350 rpm and pH range of 7.5 to 10.7

pH	Electrical Current Density (mA/cm^2)	NSRE %	CRE %	THRE %
7.6	5.86	3.5	76.02	40.62
7.8	9.77	3.92	93.63	47.95
8.2	11.72	9.59	93.96	53.30
8.7	13.67	16.77	94.92	54.00
9.2	15.63	19.48	96.45	55.00
9.5	17.58	22.82	96.82	60.00
9.8	19.53	23.41	96.88	61.25
10.1	21.48	23.11	97.51	64.80
10.4	23.44	25.66	97.59	70.47
10.7	25.39	39.54	97.76	76.92
9.7	27.34	28.89	97.72	65.00
9.6	29.29	28.58	97.69	61.60

Effect of electrolysis time on NSRE %, CRE % and THRE %

The rate of release of Al^{3+} ions from the aluminum electrode is determined from the electrolysis time (Safari et al. 2016). The effect of electrolysis time on NSRE %, CRE % and THRE % was studied over time periods of 30, 60 and 90 min at an optimum current dose of 13 A and the obtained results are given in Figure 5. As shown in Figure 5. increasing the electrolysis time improves the NSRE %, CRE % and THRE % over a period of 60 min and then stabilizes despite increasing the electrolysis time to 90 min.

This improvement in NSRE%, CRE% and THRE% with increasing electrolysis time from 30 to 60 min can be attributed to the increase in the concentration of Al^{3+} ions and their agglomerates $Al(OH)^3$ which is accompanied by an acceleration in the amount of H_2 and O2 bubble production similar to previous related studies (Holt et al. 2002; Nwabanne et al. 2018; Şık et al. 2017).

However, the amount of coagulant is directly proportional to the electrolysis time according to Faraday's law (Igwegbe et al. 2021).

Figure 5. shows that, the NSRE, CRE % and THRE % values did not change from the estimated values after 60 minutes despite increasing the electrolysis time to 90 min. This may be because the amount of contaminants in the press-water sample was completely removed in the 60 minute time period. Also, the removal efficiency of pollutants did not change when the electrolysis time exceeded the optimum time (60 min) as there was sufficient concentration of accumulated flocs to remove the pollutants present in agreement with a previous study (Abdulrazzaq et al., 2021).
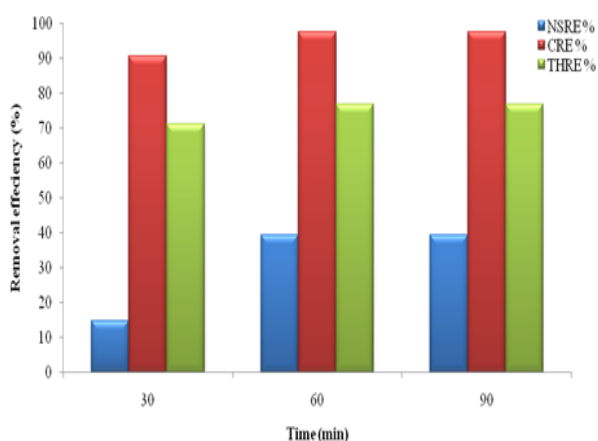

Figure 5. Effect of electrolysis time on NSRE%, CRE % and THRE %; at room temperature, S/V ratio 12.8 m-1, 350 rpm, CD 25.39 mA/cm^2 and pH 10.7 for 2Al-2Fe model.

Effect of stirring speed on NSRE %, CRE % and THRE %

Agitating the solution components in the EC cell vessel is an important factor in increasing the efficiency of contaminant removal processes. This is because stirring leads to homogeneity in the distribution of components in the reaction vessel (Bayar et al. 2011).

Stirring also increases the movement of ions in the solution, which in turn increases the kinetic energy of the reactants, leading to an increase in pollutants removal efficiency (Boinpally et al. 2023). In this regard, the effectiveness of stirring showed dependence on the speeds used which in turn accelerate or inhibit the rate of pollutants removal efficiency.

In this context, many researchers have conducted numerous investigations on the effect of stirring speed on

the removal of contaminants such as color from aqueous solutions (O'Sullivan et al. 2010; Kondusamy and Kalamdhad, 2014; Abbasi et al. 2020).

In the present study, the removal efficiencies of different pollutants, NSRE%, CRE% and THRE% were studied at stirring speeds of 0, 250, 350 and 450 rpm for a time period of 60 min, current dosage of 13 A and pH of 10.7; the results obtained are shown in Figure 6. As shown in Figure 6. increasing the stirring speed from 0 to 350 rpm shows obvious improvement in NSRE%, CRE% and THRE%.

These results can be explained by the fact that increasing the stirring speed leads to an increase in the particles collision rate and also leads to an increase in the anodic and cathodic reactions rates, which in turn leads to an increase in the formation rate of both $Al(OH)^3$ and H2.

In this regard, high agitation speed enhances the ability of the coagulant, $Al(OH)^3$, to bind pollutants through particles collision, and thus generating more agglomerates (flocs) (Fadhila et al. 2024).

On the other hand, increasing the stirring speed from 350 to 450 rpm, resulted in a decrease in the values of NSRE%, CRE% and THRE% (Figure 6).

These results can be attributed to the fact that high speeds may lead to severe collision between the particles of the formed aggregates.

This leads to their destruction and decrease in their quantity in the medium, which leads to a decrease in the efficiency of removing pollutants. (Liu et al. 2021).

Similar behavior has been reported for several cases that study the impact of the speed of stirring on the pollutants removal efficiency (O'Sullivan et al. 2010; Kondusamy and Kalamdhad, 2014; Abbasi et al. 2020; Liu et al. 2021; Boinpally et al. 2023; Fadhila et al. 2024).
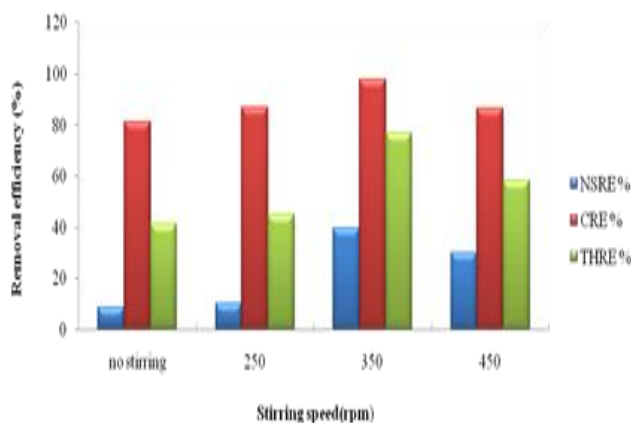

Figure 6. Effect of stirring speed on NSRE %, CRE % and THRE%; at room temperature, S/V ratio 12.8 m^{-1}, 60 min, CD 25.39 mA/cm2 and pH 10.7 for 2Al-2Fe model

Effect of anode and cathode material type

It is well known that the type of cathode and anode of the electrocoagulation cell used in pollutants removal processes greatly affects the performance efficiency.

It is known that the type of cathode and anode material in the electrocoagulation cell used in pollutants removal processes greatly affects the performance efficiency.

Due to their wide availability, low cost, and high solubility, Fe and Al are the most widely used electrodes in wastewater treatment. Recent studies show that the use of hybrid electrodes such as iron and aluminum in electrocoagulation cells gives better results (Kobya et al. 2020).

In the search for an electrocoagulation system that provides good efficiency, three models of electrocoagulation cells were designed depending on the type of electrode material used. For the first model it is of the hybrid type, the anode is of aluminum and the cathode is of iron (Al-Fe), while for the second (Al-Al) and third (Fe-Fe) models the two electrodes are of the same type.

A series of experiments were conducted to determine NSRE%, CRE% and THRE% for a time period of 60 minutes and an electrical current intensity of 13 A at pH 10.7. Figure 6 shows, that for both NSRE% and CRE% the efficiencies of the three studied models follow the order (Al-Al) > (Al-Fe) > (Fe-Fe). For The results of the present study are comparable with other similar studies on the effect of electrode material in electrocoagulation cells used for the removal of industrial wastewater pollutants (Boinpally et al. 2023). In short, the Al-Al and Al-Fe models are more efficient than the Fe-Fe model due to the higher coagulation efficiency of aluminum compared to iron (Boinpally et al. 2023).
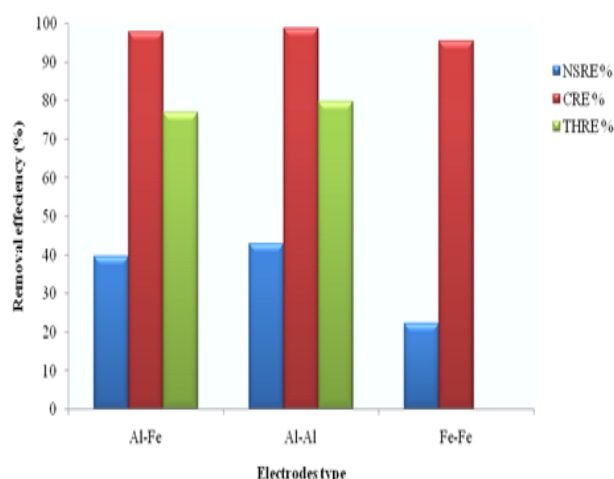

Figure 7. Effect of electrodes type on NSRE %, CRE % and THRE%; at room temperature, S/V ratio 12.8 m-1, 60 min, 350 rpm, CD 25.39 mA/cm2 and pH 10.7 .

Effect of electrode plates number

The efficiency of pollutants removal by electrocoagulation depends strongly on the amount of Al^{3+} ions released from the anode (Boinpally et al. 2023), which in turn depends on the surface area of the Al electrode immersed in the analyzed press-water sample. To investigate the effect of the surface area of electrodes used in the coagulation cell on NSRE%, CRE% and THE%, two electrode models were used.

The first model consists of two aluminum plates for the anode and two iron plates in case of the cathode. For the second model, both the anode and cathode consist of three plates of aluminum and iron respectively. All the running experiments were performed under optimum conditions for electrolysis time of 30 and 60 min and electrical current intensity value of 13 A and the results obtained are given in Table 4.

The results in Table 4. indicate that increasing the number of electrode plates used in electrocoagulation cells did not significantly affect NSRE%, CRE% and THRE%. On the other hand, a previous study indicated that the pollutant removal efficiency increased with increasing the number of EC electrode plates (Khaled et al. 2019).

This result can be explained by the fact that the surface area of the electrodes of the first model is suitable for the amounts of Al^{3+} ions emitted from the anode and OH^- ions generated at the cathode which are sufficient to remove the pollutants present in the press-water sample under study. Therefore there is no need to increase the surface area by using electrodes with a larger number of plates as in the case of the second model.

However, the number of electrode plates is a major factor to consider when designing an electrocoagulation cell reactor (Khaled et al., 2019).

Table 4. Effect of number of electrode plates on NSRE%, CRE % and THRE %; at room temperature, S/V ratio 12.8 m^{-1}, 350 rpm, CD 25.39 mA/cm^2 and pH 10.7

Electrode model	NSRE %	CRE	THRE
First model (two plats per electrode)*	29.32	90.57	68.50
Second model (three plats per electrode)*	30.74	95.68	71.30
First model (two plats per electrode)**	39.54	97.76	76.92
Second model (three plats per electrode)**	41.21	98.77	78.88

The electrolysis time is 30* and 60** minutes and the electrical current intensity is 13 A

Effect of S/V ratio

The S/V ratio is a very important factor in the design of electrochemical cells used in water purification from dissolved wastes (Khaled et al. 2019).

This ratio is calculated by dividing the effective surface area of the working electrode by the volume of the solution being analyzed.

The importance of the S/V ratio is highlighted when using electrocoagulation cells to treat wastewater, as its increase is inversely proportional to the density of the current consumed (Belhout et al. 2010). Therefore, it is necessary to take this ratio into account when estimating the costs of performing wastewater treatment operations.

In the present study, two electrocoagulation systems were designed that achieved S/V ratio values of 12.8 and 19.2 m^{-1}. The effect of S/V values on NSRE %, CRE % and THRE % was studied for an electrical current intensity values of 12, 13 and 14 A and the obtained results are tabulated in Table 5.

Table 5. Effect of S/V at differ current intensity on NSRE %, CRE % and THRE%; at room temperature, 60 min, 350 rpm, and pH 10.7 in the case of 2Al-2Fe model

Current intensity (A)	NSRE %		CRE %		THRE %	
	(12.8)*	(19.2)*	(12.8)*	(19.2)*	(12.8)*	(19.2)*
12	25.66	30.73	97.59	97.78	70.47	74.00
13	39.54	40.52	97.76	98.12	76.92	79.32
14	28.89	38.79	97.72	98.01	65.00	72.65

*S/V value (m^{-1})

The results recorded in Table 5. and Figure 3.6 indicate that within 60 minutes of electrolysis time, increasing the applied current from 12 to 13 or 14 A resulted in an increase in the S/V ratio from 12.8 to 19.2 m^{-1} which in turn resulted in a significant increase in both NSRE% and THRE%.

 These results are in a good agreement with other relevant investigations (Khaled et al. 2019). A survey in the literature indicates that increasing the S/V ratio leads to a decrease in current density consumption and improving the pollutants removal efficiency (Belhout et al. 2010). The positive results from increased S/V ratio are due to better chemical decomposition of aluminum which in turn leads to increased NSRE% and THRE%. For CRE%, there was no significant change as a result of increasing the S/V ratio values from 12.8 to 19.2 m^{-1} and also at all applied current intensity values. This result indicates that the color removal efficiency at these values of S/V ratio is ideal and consistent with the values of other operating factors. It is also noted from the data in Table 5. and Figure 8. that there is an increase in the value of both NSRE % and THRE% as a result of
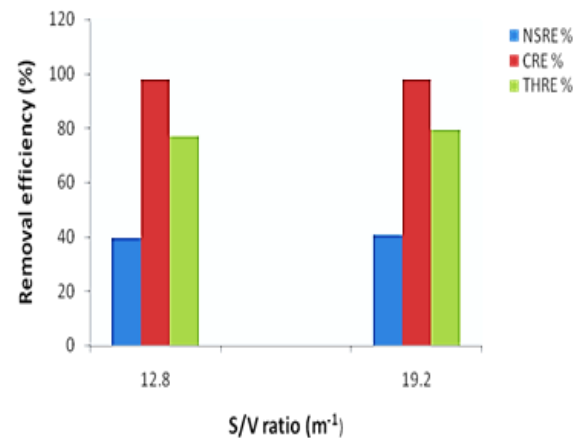

Figure 8. Effect of S/V with values of 12.8 and 19.2 m-1 for current intensity of 13 A on NSRE %, CRE % and THRE%; at room temperature, 60 min, 350 rpm, and pH 10.7 for 2Al-2Fe model

increasing the electrical current intensity from 12 to 13 A in the case of S/V ratio values of 12.8 and 19.2 m^{-1}.

On the other hand, the decrease in NSRE% and THRE% at 14 A may be due to the passivation on the iron electrode due to the precipitation of CaCO$_3$ on the surface of cathode. One of the biggest operational problems related to electrocoagulation technology is the passivation of the electrodes, which has been shown to hinder the continuity of the process and shorten its life.

The passivation of iron and aluminum electrodes in various electrocoagulation processes has been reported in several studies (Osipenko and Pogorelyi, 1977; Nikolaev et al. 1982; Novikova et al. 1982).

Electrical energy consumption (EEC)

The formation of coagulants with less energy consumption during the removal of non-sugar wastes from sugar beet press-water is a very important factor. In this regard, the effect of current operating parameters on electrical energy consumption (EEC) corresponding to the highest values of NSRE%, CRE% and THRE% achieved was studied.

In this context, EEC was calculated from the following relationship (Garcia-Segura et al., 2017)

EEC (Kwh/m^3) = EIT/V   (14)

where E, I, T, and V are the voltage (V), external applied electrical current (A), electrocoagulation time (hour), and volume of treated water (liter), respectively.

In the same regard, the electrode consumption was determined based on equation (8).

Effect of S/V ratio on anode and electrical energy consumption (EEC)

To investigate the effect of S/V ratio on EEC of the ongoing electrocoagulation experiments, the S/V ratio was changed from 12.8 to 19.2 m^{-1} with other operating parameters fixed at the values listed at the bottom of Table 6. The data in Table 6. and Figure 9. indicate an inverse relationship between the EEC (Kwh/m^3) value and the S/V m^{-1} ratio.

This result indicates that under current operating conditions, the design of the electrocoagulation cell is optimal in saving the electrical energy used. In the same context, the results in Table 6. and Figure 9. show that the change in the consumption of the aluminum anode as a result of the change in the value of the S/V ratio from 12.8 to 19.2 m^{-1} is 0.05 kg/m3 and it is small value.

In the same regard, the effect of the applied S/V ratios on the experimental and theoretical mass loss of anode was determined according to Faraday's law (Table 6.).

As shown in Table 6. the determined experimental mass loss values are higher than expected theoretically.

The calculated Faradic efficiencies corresponding to S/V ratio values of 12.8 and 19.2 m^{-1} are 119.6 and 127.9, respectively.

These findings could be attributed to the formation of Al^{3+} ions due to the electrochemical dissolution of the anodic aluminum electrode in similarity to the results reported previously (Picard et al. 2000; Singh and Ramesh, 2014).

Table 6. Effect of S/V ratio on anode and electrical energy consumption (EEC) when achieving optimum removal efficiency for current electrocoagulation processes; at room temperature, 60 min, 350 rpm, 25.39 mA/cm², pH 10.7 for 2Al-2Fe model

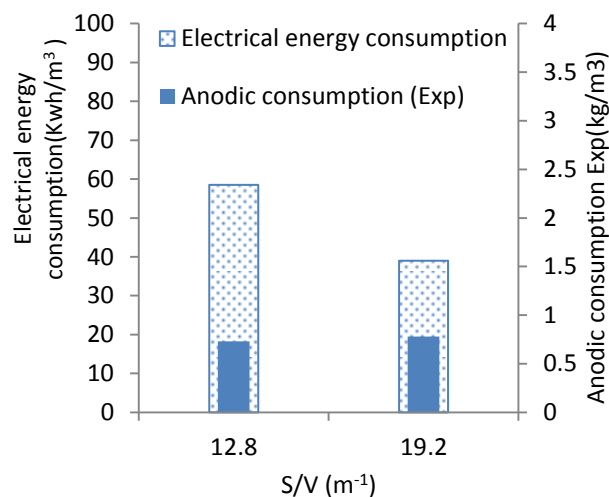| (S/V) m^{-1}	Anodic consumption kg/m³		Faradic efficiency %	Removal efficiency %			EEC (Kwh/m³)
	(Theo.)	(Exp.)		NSRE	CRE	THRE	
12.8	0.61	0.73	119.6	39.54	97.76	76.92	58.5
19.2	0.61	0.78	127.9	40.52	98.12	79.32	39.00

Figure 9. Effect of S/V ratio on anode and electrical energy consumption (EEC) upon achieving optimum removal efficiency; at room temperature, 60 min, 350 rpm, 25.39 mA/cm², pH 10.7 for 2Al-2Fe model.

Effect of electrical current density on the anode electrical energy consumption (EEC)

Since the electric current density (CD) is the most important operating parameter in the electrocoagulation process for wastewater treatment, it is necessary to study its effect on the consumption of both anode and electrical energy used. To verify the effect of current density on consumption of both electrical power and aluminum electrode, three values of CD were applied during the EC experiments and the results obtained are presented in Table 7. and Figure 10.

Data in Table 7. and Figure 10. show that raising the electrical current density leads to an increase in the consumption of aluminum electrode (anode) and electrical energy used and at the same time, an increase in the removal efficiency of the waste under study. The determined experimental values of the aluminum electrode consumption are 0.65, 0.73 and 0.82 kg/m³.

The corresponding energy consumption values are 48.0, 58.5 and 119.0 kWh/m3, while the current density values are 23.44, 25.39 and 27.34 mA/cm² respectively.

In the same context, the theoretical values of the mass consumption of the aluminum electrode show a linear proportion to the electrical current density and this leads to Faradic efficiency above 100% (Table 7.).

This result can be explained by the fact that with increasing CD, the solubility of aluminum given to the medium increases according to the results reported in the literature (Yılmaz et al. 2008; Bayar et al. 2014).

The electrical energy consumption values were determine based on equation (14) with the help of the experimental findings corresponding to the electrical current densities used (Table 7.). Table 7. shows that the calculated values of power consumption increase with increasing CD and increasing voltage difference applied to the system.   The observed increase in power consumption associated with increased CD can also be attributed to increased polarization at the electrodes (El-Shazly et al. 2011). The trend of the current results is consistent with the results of similar studies published in the literature (Gao et al. 2005; Cheng, 2006; Bayar et al. 2014).

Table 7. Effect of (CD) on anodic and electrical energy consumption; at room temperature, 60 min, 350 rpm, and S/V ratio of 12.8 cm-1 for 2Al-2Fe mode

Current(A)	(CD)* mA/cm2	Anodic consumption kg/m3		FE** %	Removal efficiency %			EEC*** (Kwh/m³)
		(Theo.)	(Exp.)		NSRE	CRE	THRE	
12	23.44	0.56	0.65	116.1	25.66	97.59	70.47	48
13	25.39	0.61	0.73	119.6	39.54	97.76	76.92	58.5
14	27.34	0.65	0.82	126.2	28.89	97.72	65.00	119

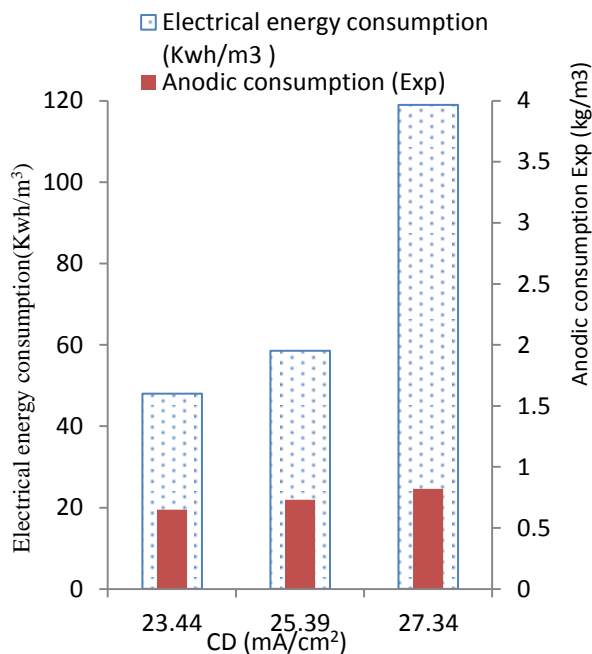*Electrical Current Density, **Faradic Efficiency, ***Electrical Energy Consumption;

Figure 10. Effect of (CD) on anodic and electrical energy consumption; at 60 min, 350 rpm, and S/V ratio of 12.8 cm-1 for 2Al-2Fe mode

Effect of types of electrode combinations and electrolysis time on the consumption of both anode and electrical energy (EEC)

The type of electrode composition and electrolysis time show a significant influence on the removal efficiency of the present study. To determine both the optimum electrodes composition and time for the electrocoagulation processes of sugar beet press-water, relevant experiments were performed at 30, 60 and 90 min for the three electrode compositions Al-Fe, Al-Al and Fe-Fe.

The results obtained are shown in Table 8. and Figure 11. with the operating parameters applied. The data in Table 8. show that for the applied three electrolysis times, the electrical energy consumption increase with increasing electrolysis time in the case of the three electrode sets investigated.

An increase in electrolysis time results in an increase in electrical energy consumption according to equation 14 where electrolysis time is directly proportional to EEC.

As shown in Table 7, the anode consumption trend follows the same behavior as the energy consumption during the three running times of the electrolysis process for the examined three electrode combinations. This behavior is consistent with Faraday's law, which states that increasing the electrolysis time results in increasing the anode mass consumption.

In the same context, the theoretical and experimental mass consumption values of the aluminum electrode show a linear proportion to the operational electrolysis time. These results give Faradic efficiency values ranging from 113.1% to 130.3%, consistent with the results of similar studies (Picard et al., 2000; Singh and Ramesh, 2014).

The data in Table 8. indicate that the 2Al-2Fe and 2Al-2Al electrode combinations show similar trends in consumption of both electrical energy and electrode mass as well as in the removal efficiency of the wastes under study.

On the other hand, although the 2Fe-2Fe electrode array consumes less electrical energy than the 2Al-2Fe and 2Al-2Al arrays, the wastewater removal efficiency percentages are lower. From comparing the results recorded in Table 8, it is clear that the 2Fe-2Fe electrodes combination is less feasible due to higher anode mass consumption and lower removal efficiency.

Table 8. Relation between anodic and electrical energy consumption and different anode - cathode types at different hydrolysis times at room temperature, 350 rpm, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1}

Electrodes Type	Time (min)	Anodic consumption kg/m^3		FE* %	Removal efficiency %			EEC** (K$_w$h/m^3)
		(Theo.)	(Exp.)		NSRE	CRE	THRE	
2Al-2Fe	30	0.31	0.39	125.8	٢٩.32	90.57	68.50	29.25
	60	0.61	0.73	119.6	39.54	97.76	76.92	58.50
	90	0.92	1.19	129.3	35.61	96.53	74.13	87.75
2Al-2Al	30	0.31	0.38	122.6	31.57	92.77	70.53	29.25
	60	0.61	0.69	113.1	42.90	98.77	79.65	58.50
	90	0.92	1.15	125.0	38.10	96.83	73.07	87.75
2Fe-2Fe	30	0.95	1.20	126.3	18.93	91.75	65.63	5.50
	60	1.89	2.30	121.7	22.23	95.53	70.53	11.00
	90	2.84	3.7	130.3	20.37	93.95	68.66	16.50

*Faradic Efficiency, **Electrical Energy Consumption
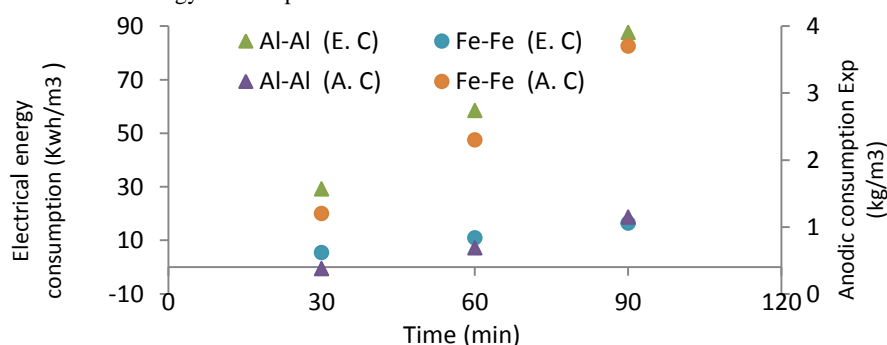
Figure 11. Relation between anodic and electrical energy consumption and different anode - cathode types at different hydrolysis times; at room temperature, 350 rpm, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1}

Effect of stirring speed on consumption of both electrical energy and anode mass

To investigate the effect of stirring speed on consumption of both electrical energy and anode mass, electrocoagulation experiments were performed at increasing speeds starting from zero and then increasing to 250, 350, and 450 rpm. On the other hand, the fixed operating parameters were S/V 12.8 m^{-1}, electrolysis time 60 min, electrical current density 25.39 mA/cm^2, and electrode composition 2Al-2Fe and the obtained results are given in Table 9. and Figure 12.

The data in Table 9. indicate that increasing the stirring speed has no significant effect on the experimental and theoretical anode mass consumption. The same trend is observed for the faradic efficiency, the value of which depends on the change in the value of the anode mass loss in the experiments carried out. On the other hand, the results in Table 9. indicate that at zero stirring speed, has no significant effect on the experimental and theoretical anode mass consumption. The same trend is

observed for the faradic efficiency, the value of which depends on the change in the value of the anode mass loss in the experiments carried out. On the other hand, the results in Table 9. indicate that at zero stirring speed, the value of the electrical energy consumed was 65.0 Kwh/m3, which decreased to 61.8 Kwh/m^3 at stirring speed value of 250 rpm. In the same context, by increasing the stirring speed to 350 rpm, the electrical energy consumed decreased to 58.5 Kwh/m3. When the stirring speed increases to 450 rpm, the electrical energy consumption increases to 68.3 Kwh/m^3, which is the highest value, recorded for the current operating stirring speeds. The effect of the stirring speed can be summarized as follows: for the present EC cell, the electrical energy is mainly consumed in formation of Al^{3+} and OH- ions at anode and cathode respectively. In the absence of stirring or at low stirring speeds, the possibility or speed of formation of Al(OH)$_3$, the main component in the pollutant removal process, decreases.

A suitable stirring speed allows quick and easy formation of $Al(OH)_3$ and consequently the removal efficiency improves, which in turn reduces the amount of energy consumed. Due to the absence of a source to achieve electrical neutrality in the present EC system as a result of Al^{3+} releasing from anode and formation of OH^- ions at cathode, polarization is expected to occur at these electrodes as well as deposition of $CaCO_3$ on cathode surface which limits his activity. This hinders the continuation of the EC process and to overcome this difficulty, the system consumes higher electrical energy. Another benefit of stirring at appropriate speeds is that it reduces the polarization that occurs around both the anode and cathode which in turn reduces electrical power consumption. When the stirring speed was increased from 350 to 450 rpm, there was an increase of energy consumption. This happens because stirring at such a high speed causes the flocs to break down, so the system has to compensate for this loss of flocs at the expense of increased energy consumption.

Table 9. Relation between anodic and electrical energy consumption and stirring speed; at room temperature, 60 min, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1} for 2Al-2Fe set

Stirring speed (Rpm)	Anodic consumption kg/m^3		FE* %	Removal efficiency %			EEC** (Kw h/m^3)
	(Theo.)	(Exp.)		NSRE	CRE	THRE	
0	0.61	0.73	119.6	8.53	81.34	41.23	65.0
250	0.61	0.73	119.6	10.11	86.69	45.12	61.8
350	0.61	0.73	119.6	39.54	97.76	76.92	58.5
450	0.61	0.73	119.6	29.89	86.54	58.42	68.3

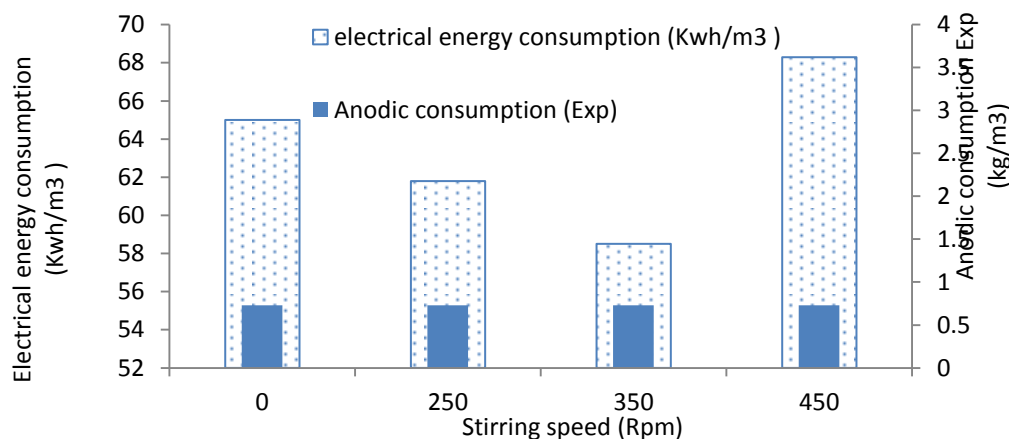*Faradic Efficiency, **Electrical Energy Consumption

Figure 12. Relation between anodic and electrical energy consumption and stirring speed at room temperature, 60 min, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1} for 2Al-2Fe set

Effect of number of electrode plates on consumption of both electrical energy and anode mass

The surface area of the electrode in electrocoagulation cells plays an important role affecting the efficiency of pollutants removal. Within the framework of the current study, two models of electrodes were designed as previously mentioned in Section 3.6. In the case of the first model, the anode consists of two aluminum plates and the cathode consists of two iron plates. Concerning the second model the anode is three plates of Al and the cathode is three plates of Fe. The EC experiments were performed at constant operating parameters of S/V 12.8 m^{-1}, electrolysis time 30 and 60 min, CD of 25.39 mA/cm^2, and stirring speed of 350 rpm and the obtained results are given in Table 10. and Figure 13.

Table 10. shows that the experimental anode mass loss value increases with the increase of the number of electrode plates of the current EC cell while the theoretical mass loss does not change. On the other hand, increasing the electrolysis time from 30 to 60 min resulted in approximately doubling the theoretical and experimental anode mass loss values. This trend of anode mass loss follows Faraday's law which states that increasing the electrolysis time results in an increase in the number of Al^{3+} ions dissolved in solution (Zaied et al. 2020).

This direct proportionality between anode mass loss and electrolysis time gives faradic efficiency ratio values above 100% in agreement with the results of similar studies (Picard et al. 2000; Singh and Ramesh, 2014). These results confirm the mechanism of the present electrochemical coagulation process for treating sugar beet press-water as shown in equations 1 to 6 in section 3.1. Regarding the relationship between energy consumption and the number of electrode plates, the data in Table 10. and Figure 13.

indicate a similar trend as in the case of anode mass loss. In this regard, increasing the anode plates from 2 to 3 increases the electrical energy consumption from 29.25 to 34.12 Kwh/m^3 and from 58.50 to 68.25 Kwh/m^3 for the electrolysis time 30 and 60 min respectively. These results are consistent with the mathematical relationship for calculating energy consumption (Eq. 14) in which the time parameter is directly proportional to the value of the electrical energy consumed.

Table 10. Effect of number of electrode plates on consumption of both electrical energy and anode mass at room temperature, 30 and 60, min, 350 rpm, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1}

Time (min)	Electrode number	Anodic consumption kg/m^3		FE* %	Removal efficiency %			EEC** Kwh/m^3
		(Theo.)	(Exp.)		NSRE	CRE	THRE	
30	2Al-2Fe	0.31	0.39	125.8	29.32	90.57	68.50	29.25
	3Al-3Fe	0.31	0.41	132.2	30.74	95.68	71.30	34.12
60	2Al-2Fe	0.61	0.73	119.6	39.54	97.76	76.92	58.50
	3Al-3Fe	0.61	0.83	136.1	41.21	98.77	78.88	68.25

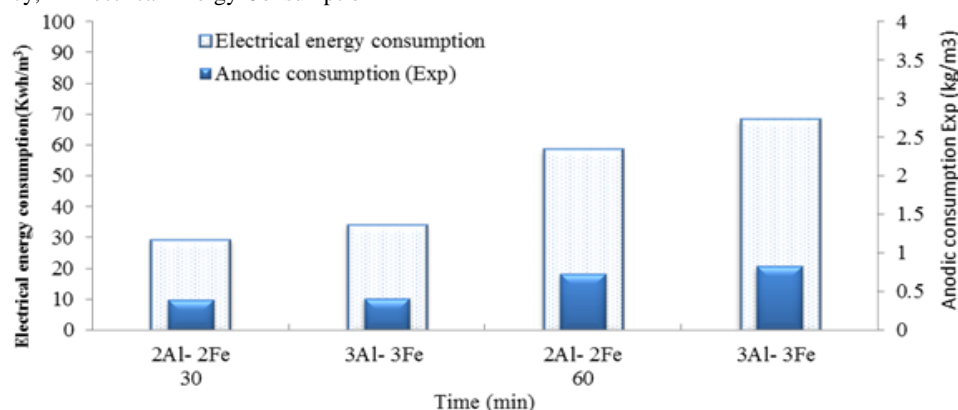*Faradic Efficiency, **Electrical Energy Consumption

Figure 13. Effect of number of electrode plates on consumption of both electrical energy and anode mass at room temperature, 30 and 60, min, 350 rpm, CD 25.39 mA/cm^2, pH 10.7 and S/V 12.8 m^{-1}

Operating cost

Economic costs are important aspects that must be taken into account when designing an electrocoagulation cell used in wastewater treatment. For the present study, the low operating cost can be estimated by considering both electrical energy consumption and electrode mass loss as major cost elements (Kobya et al. 2016). In this regard, the operating cost of the present EC process is calculated from the following relationship:

Operating cost = α Cenergy + β Celectrode +D

where Cenergy (kWh/m3) is the energy consumption and Celectrode (kg/m^3) is the electrode mass loss and these items are calculated by means of the relations 8 and 14. Unit prices α and β are given from the Egypt market are

the electrical energy price (1.4 L.E. /kWh) and aluminum-rod electrode price (1.7 L.E. /kg). D is the cost of chemicals used and is zero for the current study which did not involve any external chemical additions to the EC cell.

Summary of the optimum numerical values of operating parameters affecting removal efficiency

The results obtained from a study of the effect of the six operating factors on the removal efficiency are summarized in Table 3.9. By conducting an experiment under the influence of the optimal selective design operation parameters, the results obtained were the best. Accordingly, the operating cost for this ideal case was calculated, which amounted to 57.06 Egyptian pounds/m^3.

Table 11. Optimum operating conditions of the EC cell designed during the present study for treating sugar beet press-water at optimal pH value of 10.7

Operating Parameter	Anodic consumption kg/m^3		FE** (%)	Removal efficiency %			EEC*** (Kwh/m^3)
	(Theo.)	(Exp.)		NSRE	CRE	THRE	
CD* (mA/cm^2) 25.39	0.61	0.73	119.6	39.54	97.76	76.92	58.5
Electrolysis time 60 min	0.61	0.73	119.6	39.54	97.76	76.92	58.5
Stirring speed 350 rpm	0.61	0.73	119.6	39.54	97.76	76.92	58.5
Electrode type Al-Al	0.61	0.69	113.1	42.90	98.77	79.65	58.5
Electrode No. 4	0.61	0.73	119.6	39.54	97.76	76.92	58.5
S/V (m^2/m^3) 19.2	0.61	0.78	127.9	40.52	98.12	79.32	39
Best results	0.61	0.76	124.6	43.32	97.95	79.80	39

*Current Density, **Faradic Efficiency, *** Electrical Energy Consumption

Conclusions

Although EC technology has been in use for a long time in wastewater treatment, there is no systematic approach to EC cell design and operation. The present study deals with the possibility of using EC technology in treating of sugar beet press-water from some impurities that hinder its reuse in the sugar extraction industry.

In this regard, an EC cell was designed and used and the effects of operating parameters that control the removal efficiency of non-sugar, color and total hardness were studied. These parameters include pH, current density, electrodes material type and numbers, electrolysis time, stirring speed and S/V ratio.

The experimental results obtained showed an interaction between these operational variables. In this regard, the highest removal efficiency of non-sugar materials, color and hardness was achieved at a current density of 25.39 mA/cm^2, electrolysis time of 60 min, stirring speed of 350 rpm, electrode materials of Al-Al type, electrode number of 4, S/V ratio of 19.2 m^2/m^3 and pH value of 10.7.

The pH value of the press-water during the EC process is a critical operating factor as it controls the formation of aluminum hydroxide species that play a key role in the adsorption of various pollutants on the surface of these colloidal particles. In this context, the pH value of 8.2 and the current density of 15.63 mA/cm^2 are the optimum operating parameters for the decolorization efficiency of press-water sample under study. The current experimental investigations indicate that the mechanism of removal of the pollutants in question is based on the release of Al^{3+} ions from the anode and the hydrolysis of water at the cathode to give OH$^-$ ions.

In the bulk of the solution, Al^{3+} ions combine with OH$^-$ ions to form various types of colloidal aluminum hydroxide. Due to the large surface area of the colloidal particles of Al(OH)$_3$ it adsorbs on its surface ions and particles of different charges. In the same context, H$_2$ and O$_2$ gases are produced as by-products of various secondary reactions in EC cells. The presence of H$_2$ gas is necessary to keep the flocs buoyant and prevent them from sinking to the bottom due to gravity. In the same regard, In the same regard, the presence of O$_2$ leads to the formation of some forms of reactive oxygen species (ROS) such as H$_2$O$_2$, HO$^{\bullet}$, O$_2^{\bullet -}$...etc., which can play an effective role in removing many toxic and non-toxic pollutants by oxidizing them.As for the mechanism of removing total hardness, it depends on the alkalinity of the medium in which the HCO$_3^-$ group turns into CO$_3^{2-}$, which combines with Ca^{2+} ion to form CaCO$_3$ precipitate that sinks to the bottom, and part of it deposit on the surface of the cathode, which hinders its activity.

This explains may clarify the decrease in removal efficiency after raising the operating parameters values above the mentioned ideal. As for the removal of the Mg^{2+} ion with the OH$^-$ ions, formed as a result of the hydrolysis of water at the cathode, to form Mg(OH)$_2$ which settles by gravity at the bottom of the EC vessel. Since sugar beet press-water is returned directly to the diffuser during sugar extraction processes, chemical or biological treatments are not suitable at all and EC treatment method is the most suitable technology for treating sugar beet press-water. Therefore, the promising results of the current study open the way in future for the design of electrocoagulation cells that can be used in the treatment of sugar beet press-water.

Acknowledgments

Reference

Abbas SH, Ali WH (2018) Electrocoagulation technique used to treat wastewater: a review. American Journal of Engineering Research, 7(10), 74-88.

Abbasi S, Mirghorayshi M, Zinadini S, Zinatizadeh AA (2020) A novel single continuous electrocoagulation process for treatment of licorice processing wastewater: Optimization of operating factors using RSM. Process Safety and Environmental Protection, 134, 323-332. https://doi.org/https://doi.org/10.1016/j.psep.2019.12.005

Abdel-Shafy HI, Shoeib MA, El-Khateeb MA, Youssef AO, Hafez OM (2020) Electrochemical treatment of industrial cooling tower blowdown water using magnesium-rod electrode. Water Resources and Industry, 23, 100121. https://doi.org/https://doi.org/10.1016/j.wri.2019.100121

Abdul Rahman N, Albania Linus A, Gilan UJ, Jihed EE, Kumar NKMF, Yassin A, Philip A (2020) Experimental study of batch electrocoagulation treatment of peat water in Sarawak with aluminium electrodes. IOP Conference Series: Materials Science and Engineering, 778(1), 012126. https://doi.org/https://doi.org/10.1088/1757-899X/778/1/012126

Abdul Rahman N, Jose Jol C, Albania Linus A, Wan Borhan WWS, Abdul Jalal NS, Baharuddin N, Samsul SNA, Abdul Mutalip NA (2023) Statistical analysis of salinity reduction in Borneo tropical brackish peat water with continuous electrocoagulation treatment system. Journal of Hazardous Materials Advances, 10, 100265. https://doi.org/https://doi.org/10.1016/j.hazadv.2023.100265

Abdulrazzaq NN, Al-Sabbagh BH, Shanshool HA (2021) Coupling of electrocoagulation and microflotation for the removal of textile dyes from aqueous solutions. Journal of Water Process Engineering, 40, 101906. https://doi.org/https://doi.org/10.1016/j.jwpe.2020.101906

Adhoum N, Monser L (2004) Decolourization and removal of phenolic compounds from olive mill wastewater by electrocoagulation. Chemical Engineering and Processing: Process Intensification, 43(10), 1281-1287. https://doi.org/https://doi.org/10.1016/j.cep.2003.12.001 .

Ahmadian M, Yousefi N, Van Ginkel SW, Zare MR, Rahimi S, Fatehizadeh A (2012) Kinetic study of slaughterhouse wastewater treatment by electrocoagulation using Fe electrodes. Water Science and Technology, 66(4), 754-760. https://doi.org/https://doi.org/10.2166/wst.2012.232

Ahmadzadeh S, Asadipour A, Yoosefian M, Dolatabadi M (2017) Improved electrocoagulation process using chitosan for efficient removal of cefazolin antibiotic from hospital wastewater through sweep flocculation and adsorption: kinetic and isotherm study. Desalination and Water Treatment, 92, 160-171. https://doi.org/https://doi.org/10.5004/dwt.2017.21492

Badakhshan S, Ahmadzadeh S, Mohseni-Bandpei A, Aghasi M, Basiri A (2019) Potentiometric sensor for iron (III) quantitative determination: experimental and computational approaches. BMC Chemistry, 13(1), 131. https://doi.org/10.1186/s13065-019-0648-x

Bayar S, Boncukcuoğlu R, Yilmaz AE, Fil BA (2014) Pre-treatment of pistachio processing industry wastewaters (PPIW) by electrocoagulation using Al plate electrode. Separation Science and Technology, 49(7), 1008-1018. https://doi.org/https://doi.org/10.1080/01496395.2013.878847

Bayar S, Yıldız YŞ, Yılmaz AE, İrdemez Ş (2011) The effect of stirring speed and current density on removal efficiency of poultry slaughterhouse wastewater by electrocoagulation method. Desalination, 280(1-3), 103-107. https://doi.org/https://doi.org/10.1016/j.desal.2011.06.061

Belhout D, Ghernaout D, Djezzar-Douakh S, Kellil A (2010) Electrocoagulation of a raw water of Ghrib Dam (Algeria) in batch using aluminium and iron electrodes. Desalination and Water Treatment, 16(1-3), 1-9. https://doi.org/https://doi.org/10.5004/dwt.2010.1081

Bhagawati PB, AlJaberi FY, Ahmed SA, Kadier A, Alwan HH, Ajjam SK, Shivayogimath CB, Babu BR (2022) Electrocoagulation Technology for Wastewater Treatment: Mechanism and Applications. In Advanced Oxidation Processes in Dye-Containing Wastewater: Volume 1 (pp. 305-318). Springer. https://doi.org/DOI: 10.1007/978-981-19-0987-0_13

Bogliolo M, Bottino A, Capannelli G, De Petro M, Servida A, Pezzi G, Vallini G (1997) Clean water recycle in sugar extraction process: performance analysis of reverse osmosis in the treatment of sugar beet press water. Desalination, 108(1-3), 261-271. https://doi.org/http://hdl.handle.net/11567/191245

Boinpally S, Kolla A, Kainthola J, Kodali R, Vemuri J (2023) A state-of-the-art review of the electrocoagulation technology for wastewater treatment. Water Cycle, 4, 26-36. https://doi.org/https://doi.org/10.1016/j.watcyc.2023.01.001

Chen G (2004) Electrochemical technologies in wastewater treatment. Separation and Purification Technology, 38(1), 11-41. https://doi.org/https://doi.org/10.1016/j.seppur.2003.10.006

Cheng H (2006) Cu(II) Removal from lithium bromide refrigerant by chemical precipitation and electrocoagulation. Separation and Purification Technology, 52(1), 191-195. https://doi.org/https://doi.org/10.1016/j.seppur.2006.03.021

Chu HC, Campbell JS, Light WG (1988) High-temperature reverse osmosis membrane element. Desalination, 70(1), 65-76. https://doi.org/https://doi.org/10.1016/0011-9164(88)85044-6

Das PP, Sharma M, Purkait MK (2022) Recent progress on electrocoagulation process for wastewater treatment: A review. Separation and Purification Technology, 292, 121058. https://doi.org/https://doi.org/10.1016/j.seppur.2022.121058

Demirci Y, Pekel LC, Alpbaz M (2015) Investigation of Different Electrode Connections in Electrocoagulation of Textile Wastewater Treatment. International Journal of Electrochemical Science, 10(3), 2685-2693. https://doi.org/https://doi.org/10.1016/S1452-3981(23)04877-0

Dolatabadi M, Meftahizade H, Ahmadzadeh S, Abbasi F, Falakian M, Ghorbanpour M (2023) Correction to: Efficiency of modified plant guar gum as aid coagulant for removal of diazinon from aqueous solution: optimization by response surface methodology. Chemical Papers, 77(4), 2327-2327. https://doi.org/https://doi.org/10.1007/s11696-022-02632-z

El-Shazly AH, Al-Zahrani AA, Al-Shahrani SS (2011) Improvement of NO3- Removal from Wastewater by Using Batch Electrocoagulation Unit with Vertical Monopolar Aluminum Electrodes. International Journal of Electrochemical Science, 6(9), 4141-4149. https://doi.org/https://doi.org/10.1016/S1452-3981(23)18316-7

Eyvaz M, Kirlaroglu M, Aktas TS, Yuksel E (2009) The effects of alternating current electrocoagulation on dye removal from aqueous solutions. Chemical Engineering Journal, 153(1), 16-22. https://doi.org/https://doi.org/10.1016/j.cej.2009.05.028

Fadhila F, Zulkarnaini Z, Husin A, Syawal FA (2024) Effect of Electrode Distance, Stirring Speed and Contact Time on Removal of Polyethylene Microplastics (Microbeads) Using Electrocoagulation Method. Elkawnie: Journal of Islamic Science and Technology, 10(1), 158-168. https://doi.org/DOI: 10.22373/ekw.v10i1.22195

Fouladgar M, Ahmadzadeh S (2016) Application of a nanostructured sensor based on NiO nanoparticles modified carbon paste electrode for determination of methyldopa in the presence of folic acid. Applied Surface Science, 379, 150-155. https://doi.org/https://doi.org/10.1016/j.apsusc.2016.04.026

Gao P, Chen X, Shen F, Chen G (2005) Removal of chromium(VI) from wastewater by combined electrocoagulation–electroflotation without a filter. Separation and Purification Technology, 43(2), 117-123. https://doi.org/https://doi.org/10.1016/j.seppur.2004.10.008

Garcia-Segura S, Eiband MMS, de Melo JV, Martínez-Huitle CA (2017) Electrocoagulation and advanced electrocoagulation processes: A general review about the fundamentals, emerging applications and its association with other technologies. Journal of Electroanalytical Chemistry, 801, 267-299. https://doi.org/https://doi.org/10.1016/j.jelechem.2017.07.047

Garg KK, Prasad B (2016) Development of Box Behnken design for treatment of terephthalic acid wastewater by electrocoagulation process: optimization of process and analysis of sludge. Journal of Environmental Chemical Engineering, 4(1), 178-190. https://doi.org/https://doi.org/10.1016/J.JECE.2015.11.012

Gekas V, HallströmB, Träg»rdh G (1985) Food and dairy applications: the state of the art. Desalination, 53, 95-127. https://doi.org/https://api.semanticscholar.org/CorpusID:110283627

Gondudey S, Chaudhari PK (2020) Influence of Various Electrode Materials in Electrocoagulation Efficiency: Application in Treatment of Sugar Industry Effluent. Sugar Tech, 22(1), 15-27. https://doi.org/https://doi.org/10.1007/s12355-019-00753-6

Gürses A, Yalçin M, Doğar C (2002) Electrocoagulation of some reactive dyes: a statistical investigation of some electrochemical variables. Waste management, 22(5), 491-499. https://doi.org/https://doi.org/10.1016/s0956-053x(02)00015-6

Hasson D, Sidorenko G, Semiat R (2011) Low electrode area electrochemical scale removal system. Desalination and Water Treatment, 31(1-3), 35-41. https://doi.org/https://doi.org/10.5004/dwt.2011.2389

Holt PK, Barton GW, Wark M, Mitchell CA (2002) A quantitative comparison between chemical dosing and electrocoagulation. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 211(2), 233-248. https://doi.org/https://doi.org/10.1016/S0927-7757(02)00285-6

Igwegbe CA, Onukwuli OD, Ighalo JO, Umembamalu CJ (2021) Electrocoagulation-flocculation of aquaculture effluent using hybrid iron and aluminium electrodes: A comparative study. Chemical Engineering Journal Advances, 6, 100107. https://doi.org/https://doi.org/10.1016/j.ceja.2021.100107

Ilhan F, Kurt U, Apaydin O, Gonullu MT (2008) Treatment of leachate by electrocoagulation using aluminum and iron electrodes. Journal of Hazardous Materials, 154(1-3), 381-389. https://doi.org/https://doi.org/10.1016/j.jhazmat.2007.10.035

Ingelsson M, Yasri N, Roberts EP (2020) Electrode passivation, faradaic efficiency, and performance enhancement strategies in electrocoagulation—a review. Water Research, 187, 116433. https://doi.org/https://doi.org/10.1016/j.watres.2020.116433

Kabdaşlı I, Arslan-Alaton I, Ölmez-Hancı T, Tünay O (2012) Electrocoagulation applications for industrial wastewaters: a critical review. Environmental Technology Reviews, 1(1), 2-45. https://doi.org/https://doi.org/10.1080/21622515.2012.715390

Kalash KR, Ghazi IN, Abdul-Majeed MA (2015) Hardness removal from drinking water using electrochemical cell. Engineering and Technology Journal, 33(1), 78-89.

Karathanos VT, Belessiotis VG (1999) Application of a thin-layer equation to drying data of fresh and semi-dried fruits. Journal of Agricultural Engineering Research, 74(4), 355-361. https://doi.org/https://doi.org/10.1006/jaer.1999.0473

Khaled B, Wided B, Béchir H, Elimame E, Mouna L, Zied T (2019) Investigation of electrocoagulation reactor design parameters effect on the removal of cadmium from synthetic and phosphate industrial wastewater. Arabian Journal of Chemistry, 12(8), 1848-1859. https://doi.org/https://doi.org/10.1016/j.arabjc.2014.12.012

Kim MK, Kim T, Kim TK, Joo SW, Zoh KD (2020) Degradation mechanism of perfluorooctanoic acid (PFOA) during electrocoagulation using Fe electrode. Separation and Purification Technology, 247, 116911. https://doi.org/https://doi.org/10.1016/j.seppur.2020.116911

Kobya M, Can OT, Bayramoglu M (2003) Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes. Journal of Hazardous Materials, 100(1), 163-178. https://doi.org/https://doi.org/10.1016/S0304-3894(03)00102-X

Kobya M, Gengec E, Demirbas E (2016) Operating parameters and costs assessments of a real dyehouse wastewater effluent treated by a continuous electrocoagulation process. Chemical Engineering and Processing: Process Intensification, 101, 87-100. https://doi.org/https://doi.org/10.1016/j.cep.2015.11.012.

Kobya M, Soltani RDC, Omwene PI, Khataee A (2020) A review on decontamination of arsenic-contained water by electrocoagulation: Reactor configurations and operating cost along with removal mechanisms. Environmental Technology & Innovation, 17, 100519. https://doi.org/https://doi.org/10.1016/j.eti.2019.100519

Kondusamy D, Kalamdhad AS (2014) Pre-treatment and anaerobic digestion of food waste for high rate methane production – A review. Journal of Environmental Chemical Engineering, 2(3), 1821-1830. https://doi.org/https://doi.org/10.1016/j.jece.2014.07.024

Kumar PR, Chaudhari S, Khilar KC, Mahajan SP (2004) Removal of arsenic from water by electrocoagulation. Chemosphere, 55(9), 1245-1252. https://doi.org/https://doi.org/10.1016/j.chemosphere.2003.12.025

Liu Y, Zhang X, Jiang WWUM, Li Z (2021) Comprehensive review of floc growth and structure using electrocoagulation: Characterization, measurement, and influencing factors. Chemical Engineering Journal, 417, 129310. https://doi.org/https://doi.org/10.1016/j.cej.2021.129310

Liu Z, Chen WWUD, Wei S, Zhu M (2022) Optimized electrocoagulation technology using response surface methodology to control H2 production and treatment effect of fracturing flowback fluid treated by electrocoagulation. Desalination and Water Treatment, 262, 74-88. https://doi.org/https://doi.org/10.5004/dwt.2022.28501

Mahroudi A, Aghasi M, Dolatabadi M, Ahmadzadeh S (2022) Removal of reactive blue 171 dye from aqueous solution and textile industrial wastewater using peroxi-electrocoagulation process by iron electrode: application of response surface methodology. Desalination and Water Treatment, 272, 266-276. https://doi.org/https://doi.org/10.5004/dwt.2022.28821

Manjunath SV, Yakshith BR, Meghashree M (2023) Synergistic analysis for co-treatment of poultry wastewater and sewage in electro-chemical system: Operational parameters, kinetics and energy estimation. Results in Engineering, 19, 101275. https://doi.org/https://doi.org/10.1016/j.rineng.2023.10127

EKB

Mao Y, Zhao Y, Cotterill S (2023) Examining current and future applications of electrocoagulation in wastewater treatment. Water, 15(8), 1455. https://doi.org/https://doi.org/10.3390/w15081455

Medina-Collana JT, Reyna-Mendoza GE, Montaño-Pisfil JA, Rosales-Huamani JA, Franco-Gonzales EJ, Córdova García X (2023) Evaluation of the Performance of the Electrocoagulation Process for the Removal of Water Hardness. Sustainability, 15(1), 590. https://doi.org/https://doi.org/10.3390/su15010590

Mohtashami R, Shang JQ (2019) Electroflotation for Treatment of Industrial Wastewaters: A Focused Review. Environmental Processes, 6(2), 325-353. https://doi.org/https://doi.org/10.1007/s40710-019-00348-z

Mollah MYA, Morkovsky P, Gomes JAG, Kesmez M, Parga J, Cocke DL (2004) Fundamentals, present and future perspectives of electrocoagulation. Journal of Hazardous Materials, 114(1), 199-210. https://doi.org/https://doi.org/10.1016/j.jhazmat.2004.08.009

Moussa DT, El-Naas MH, Nasser M, Al-Marri MJ (2017) A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. Journal of Environmental Management, 186, 24-41. https://doi.org/https://doi.org/10.1016/j.jenvman.2016.10.032

Naje AS, Chelliapan S, Zakaria Z, Ajeel MA, Alaba PA (2017) A review of electrocoagulation technology for the treatment of textile wastewater. Reviews in Chemical Engineering, 33(3), 263-292. https://doi.org/https://doi.org/10.1515/revce-2016-0019

Nandi BK, Patel S (2017) Effects of operational parameters on the removal of brilliant green dye from aqueous solutions by electrocoagulation. Arabian Journal of Chemistry, 10, S2961-S2968. https://doi.org/https://doi.org/10.1016/j.arabjc.2013.11.032

Nidheesh P, Singh TA (2017) Arsenic removal by electrocoagulation process: Recent trends and removal mechanism. Chemosphere, 181, 418-432. https://doi.org/https://doi.org/10.1016/j.chemosphere.2017.04.082

Nielsen WK, Kristensen S, Madsen RF (1982) Prospects and possibilities in application of membrane filtration systems within the beet and cane sugar industry. [Review article].

Nikolaev N, Kozlovskii A, Utkin I (1982) Treating natural waters in small water systems by filtration with electrocoagulation. Soviet Journal of Water Chemistry and Technology, 4(3), 244-247.

Noghabi MS, Razavi SMA, Mousavi SM, Elahi M, Niazmand R (2011) Effect of operating parameters on performance of nanofiltration of sugar beet press water. Procedia Food Science, 1, 160-164. https://doi.org/https://doi.org/10.1016/j.profoo.2011.09.025

Novikova S, Shkorbatova T, Sokol EY (1982) Purification of effluents from the production of synthetic detergents by electrocoagulation. Soviet J. Water Chem. Technol, 4(4), 353-357.

Nwabanne JT, Oguegbu OO, Agu CM (2018) Removal of solids from palm oil mill effluent and paint wastewater using electrocoagulation technique. International Journal of Electrochemistry, 2018(1), 4349639. https://doi.org/https://doi.org/10.1155/2018/4349639

O'Sullivan C, Rounsefell B, Grinham A, Clarke W, Udy J (2010) Anaerobic digestion of harvested aquatic weeds: water hyacinth (Eichhornia crassipes), cabomba (Cabomba Caroliniana) and salvinia (Salvinia molesta). Ecological Engineering, 36(10), 1459-1468. https://doi.org/https://doi.org/10.1016/j.ecoleng.2010.06.027

Osipenko VD, Pogorelyi PI (1977) Electrocoagulation neutralization of chromium containing effluent. Metallurgist, 21(9), 628-630. https://doi.org/https://doi.org/10.1007/BF01083218

Ozyonar F, Karagozoglu B (2011) Operating cost analysis and treatment of domestic wastewater by electrocoagulation using aluminum electrodes. Pol. J. Environ. Stud, 20(1), 173.

Patel RK, Shankar R, Khare P, Mondal P (2022) Treatment of sugar processing industry wastewater using copper electrode by electrocoagulation: Performance and economic study. Journal of the Indian Chemical Society, 99(8), 100563. https://doi.org/https://doi.org/10.1016/j.jics.2022.100563

Picard T, Cathalifaud-Feuillade G, Mazet M, Vandensteendam C (2000) Cathodic dissolution in the electrocoagulation process using aluminium electrodes. Journal of Environmental Monitoring, 2(1), 77-80. https://doi.org/https://doi.org/10.1039/A908248D

Pirkarami A, Olya ME (2017) Removal of dye from industrial wastewater with an emphasis on improving economic efficiency and degradation mechanism. Journal of Saudi Chemical Society, 21, S179-S186. https://doi.org/https://doi.org/10.1016/j.jscs.2013.12.008

Pooja K, Salkar V (2017) Review of studies on hardness removal by electrocoagulation. Int J Eng Res Technol, 10(1), 309-313.

Rumky J, Deb A, Shim MJ, Laakso E, Repo E (2023) A review on the recent advances in electrochemical treatment technologies for sludge dewatering and alternative uses. Journal of Hazardous Materials Advances, 11, 100341. https://doi.org/https://doi.org/10.1016/j.hazadv.2023.100341

Safari S, Azadi Aghdam M, & Kariminia HR (2016) Electrocoagulation for COD and diesel removal from oily wastewater. International Journal of Environmental Science and Technology, 13, 231-242. https://doi.org/https://doi.org/10.1007/s13762-015-0863-5

Sahu O (2019) Suitability of chemical and electrocoagulation process on sugar industry wastewater treatment. International Journal of Energy and Water Resources, 3(2), 117-125. https://doi.org/https://doi.org/10.1007/s42108-019-00021-z

Sahu O, Mazumdar B, Chaudhari P (2014) Treatment of wastewater by electrocoagulation: a review. Environmental science and pollution research, 21, 2397-2413. https://doi.org/https://doi.org/10.1007/s11356-013-2208-6

Sediqi S, Bazargan A, Mirbagheri SA (2021) Consuming the least amount of energy and resources in landfill leachate electrocoagulation. Environmental Technology & Innovation, 22, 101454. https://doi.org/https://doi.org/10.1016/j.eti.2021.101454

Sharma D, Chaudhari PK, Prajapati AK (2020) Removal of chromium (VI) and lead from electroplating effluent using electrocoagulation. Separation Science and Technology, 55(2), 321-331. https://doi.org/https://doi.org/10.1080/01496395.2018.1563157

Sharma S, Simsek H (2020) Sugar beet industry process wastewater treatment using electrochemical methods and optimization of parameters using response surface methodology. Chemosphere, 238, 124669. https://doi.org/https://doi.org/10.1016/j.chemosphere.2019.124669

Şık E, Demirbas E, Goren AY, Oncel MS, Kobya M (2017) Arsenite and arsenate removals from groundwater by electrocoagulation using iron ball anodes: Influence of operating parameters. Journal of Water Process Engineering, 18, 83-91. https://doi.org/https://doi.org/10.1016/j.jwpe.2017.06.004

Singh TSA, Ramesh ST (2014) An experimental study of CI Reactive Blue 25 removal from aqueous solution by electrocoagulation using Aluminum sacrificial electrode: kinetics and influence of parameters on electrocoagulation performance. Desalination and Water Treatment, 52(13-15), 2634-2642. https://doi.org/https://doi.org/10.1080/19443994.2013.794714

TolgaYılmaz M, Bayar S, Özcan S (2018) Treatment of sugar industry wastewater by electrocoagulation using Fe and Al electrodes: a comparative study. Desalination and Water Treatment, 131, 206-211. https://doi.org/https://doi.org/10.5004/dwt.2018.23052

van der Poel P, Schiweck H, Schwartz T (1998) Sugar technology, beet and cane sugar manufacture. (No Title).

Wang W, Chen Q, Lin W, Zheng X, Xu J, Yu J (2021) Effect of operational parameters and material properties on hardness removal efficiency by electrochemical technique. Water Supply, 21(7), 3437-3448. https://doi.org/https://doi.org/10.2166/ws.2021.105

Yaqub A, Raza H, Ajab H, Shah SH, Shad A, Bhatti ZA (2023) Decolorization of reactive blue-2 dye in aqueous solution by electrocoagulation process using aluminum and steel electrodes. Journal of Hazardous Materials Advances, 9, 100248. https://doi.org/https://doi.org/10.1016/j.hazadv.2023.100248

Yılmaz AE, Boncukcuoğlu R, Kocaker MM, Kocadağistan E (2008) An empirical model for kinetics of boron removal from boroncontaining wastewaters by the electrocoagulation method in a batch reactor. Desalination, 230(1-3), 288-297. https://doi.org/https://doi.org/10.1016/j.desal.2007.11.031

Zaied B, Rashid M, Nasrullah M, Zularisam A, Pant D, Singh L (2020) A comprehensive review on contaminants removal from pharmaceutical wastewater by electrocoagulation process. Science of the Total Environment, 726, 138095. https://doi.org/https://doi.org/10.1016/J.SCITOTENV.2020.138095

Zhi S, Zhang S (2014) A novel combined electrochemical system for hardness removal. Desalination, 349, 68-72. https://doi.org/https://doi.org/10.1016/j.desal.2014.06.02