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Electrocoagulation Technique Used To Treat Wastewater: A Review

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ABSTRACT: *Electrocoagulation is a process that has a great ability to remove wastes from water due to its high decolourization efficiency, economically attractive and relatively little sludge formation compared with other tradition processes such as biological, physical, chemical , adsorption and advanced oxidation processes. Electrocoagulation process is effective in removing a wide range of impurities like color, COD, BOD, turbidity, and metal ions removal from wastewater. This review paper is focus on various studies on treatment of industrial wastewater by Electrocoagulation method depending on the mechanisms and several affected factors such as pH, current density, applied voltage, agitation speed, type, size and number of electrodes, inter electrode distance, initial concentration and electrolysis time which have been published in journals. Electrocoagulation process has been proposed as alternative method to biological, physical and chemical methods due to its environmental friendly and cheap to operate.*

KEYWORDS:*Electrocoagulation, Electrodes, Wastewater, removal efficiency, Electrolyte*

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I. INTRODUCTION

Effluents from many industries are now one of the major sources of water pollution which represent important environmental problems [1]. These pollutants in water causes considerable damage to the aquatic environment [2] and significant source of environmental pollution [3][4].It contains several harmful chemicals that are toxic to biological life [5]. The reuse of wastewater has become an absolute necessity and un urgent need to develop inexpensive techniques for treatment of wastewater. A number of conventional treatment techniques have been applied to overcome this problem such as catalytic oxidation, adsorption processes, ion exchange, biological processes, membrane separation processes, advanced oxidation processes, ultrafiltration, chemical precipitation, reverse osmosis, photocatalysis, chemical coagulation and electrocoagulation [6][7]. Most of these methods are effective, although they are quite expensive and have many disadvantages and limitations [8]. Electrocoagulation (EC) is a promising technique for removal of pollutants from wastewater due to its simple, cheap to operate, easily available equipment and environmental friendly [9]. But it has received little scientific attention [10]. This process has the potential to extensively eliminate the disadvantages of the classical treatment techniques. Moreover, the mechanisms of EC are yet to be clearly understood and there has been very little consideration of the factors that influence the effective removal of ionic species particularly heavy metal ions , oil wastes, foodstuff, suspended particles, polymeric wastes, phenolic wastes, arsenic, textile and dyes from wastewater by this technique [10][11] .

In the current review article, an attempt has been made to discuss the electrocoagulation method to remove different pollutants from water and wastewater treatment plants.

II. ELECTROCOAGULATION (EC)

2.1 Definition of Electrocoagulation

Electrocoagulation is an alternative electrochemical treatment method which has gained increasing attention in recent years due to its simple operation, high removal efficiency, little sludge produced and requiring less chemicals [12][13]..It is regarded as a potentially effective method for treating many types of wastewater with high decolorization efficiency and relatively little sludge formation [14]

Electrocoagulation (EC) is a unique method for water and wastewater treatment that is based on the electrochemical dissolution of sacrificial metal electrodes into soluble or insoluble species that improves the coagulation, the adsorption or the precipitation of soluble or colloidal pollutants with high removal efficiency [15][16].

Electrocoagulation process involves applying an electric current to sacrificial electrodes (mostly iron and aluminum) inside a reactor tank where the current generates a coagulating agent and gas bubbles [17].

In EC, differences in electric potentials are used to generate coagulants which can remove color, suspended and dissolved particles in wastewater [18].

This technique is an indirect electrochemical method which produces coagulant agents (Fe^{+3}or Al^{+3}) from the electrode material (Fe or Al) in hydroxide medium. These species, that is,Fe $(OH)_{3}$, can remove dissolved pollutants by precipitation or by floatation [19][20].These complex compounds are attached to the bubbles of H_2 (gas) evolved at the cathode and transported to the top of solution.

Electrocoagulation (EC) also known as radio frequency diathermy or short wave electrolysis is fast becoming popular as an alternative method for the treatment of water and wastewater. The process is applied when removal of pollutant by chemical coagulation becomes difficult or impossible [21][22]. EC is an advanced economical water treatment process that has been shown to be effective in removing suspended solids, depolluting heavy metals and breaking down emulsifiers [23][24].

1.2 Principles of Electrocoagulation

The electrocoagulation technique uses an electrochemical cell to treat the water. In the simplest form, an electrochemical cell consists of two electrodes, the anode and the cathode, immersed in a conducting solution or the electrolyte and connected together via an electrical circuit which includes a current source and control device, as shown in Figure 1[25].

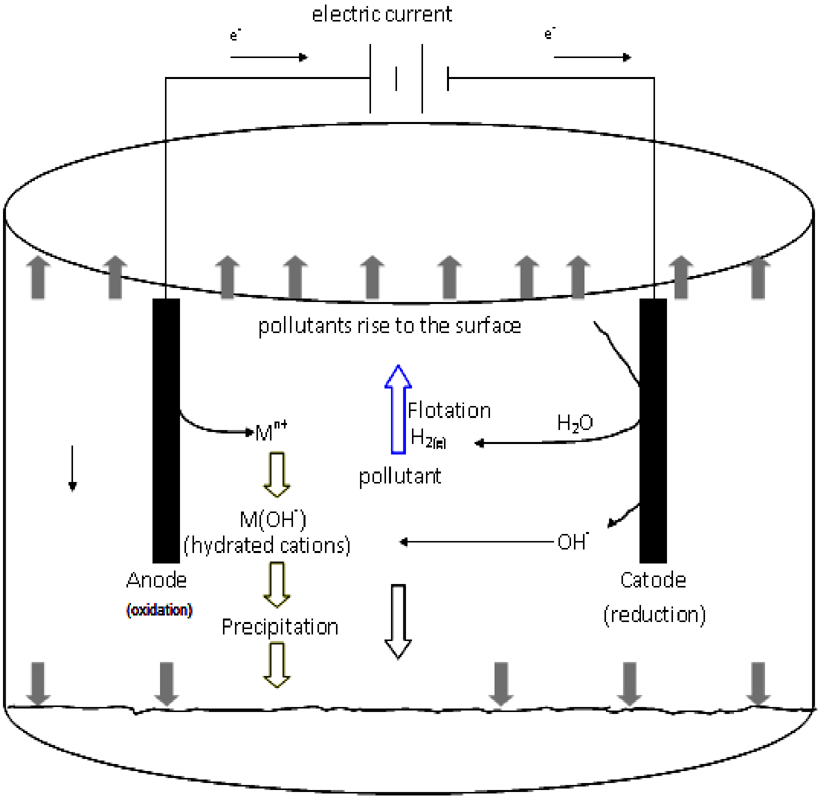

Figure 1. Schematic diagram of an electrocoagulation cell with two electrodes [25].

The metallic cations, generated from the anode, hydrolyze to form hydroxides, poly hydroxides and poly hydroxyl metallic compounds with a strong affinity for dispersed particles and counter ions, thus causing coagulation. Indeed, they can reduce the net surface charge of colloidal particles that are in suspension due to the reduction of the repulsive potential of the electrical double layer. As a result, the repulsive forces between the colloidal particles decrease and this brings the particles sufficiently close so that the van der Waals forces predominate and agglomeration of the particles occurs. It is worth noting that in electrocoagulation the processes of coagulation and flocculation occur simultaneously and it is not possible to distinguish between the two stages as in chemical coagulation. Indeed, when metal salts are used in water treatment facilities, the two stages, coagulation and flocculation, are physically separated or differentiated on the basis of the time required for each of the processes[26][27]..

2.3Theory of Electrocoagulation

The theory of EC has been discussed by a number of authors. Electrocoagulation (EC) is a complicated process involving many chemical and physical phenomena that use consumable electrodes to supply ions into the wastewater stream. In an EC process the coagulating ions are produced ‘in situ’ it involves the following successive stages [28]

1- Formation of coagulants by electrolytic oxidation of sacrificial electrode.
2- Formation of OH^- ions and H_2 at the cathode
3- Electrolytic reactions at the electrode surfaces
4- Destabilization of contaminants, particulate suspension and breaking ofemulsions
5- Aggregation of destabilized phases to form flocs
6- Removal of colloids by sedimentation or flotation

Destabilization mechanism in EC process plays an important role; it contains the following steps [28]:

1. Compression of the diffuse double-layer around the charged species, which is achieved by the interactions of ions generated by dissolution of the sacrificial electrode, due to passage of current through the solution.
2. Charge neutralization of the ionic species present in wastewater, which is caused by the counter ions, produced by the electrochemical dissolution of the sacrificial electrode. These counter ions reduce the electrostatic inter-particle repulsion sufficiently so that the van der Waals attraction predominates, thus causing coagulation. A zero net charge results in the process.
3. Floc formation, the floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles that have not been completed.

The solid oxides, hydroxides and oxhydroxides provide active surfaces for the adsorption of the polluting species. Electrocoagulation has been successfully employed in removing metals, suspended particles, clay minerals, organic dyes, and oil and greases from a variety of industrial effluents. In this process, a potential is applied to the metal anodes, typically fabricated from either iron or aluminum

2.4Mechanisms of Electrocoagulation Process

The chemical processes occurring in the cell are oxidation and reduction reactions, which take place at the electrode/electrolyte interface. The electrode at which reduction occurs is referred as the cathode, whereas the anode is the electrode at which oxidation processes occur. The anode, also called the sacrificial electrode, corrodes to release active coagulant cations, usually aluminum or iron, to the solution. Consequently, electrocoagulation introduces metal cationsin situ, rather than by external dosing. Simultaneously, electrolytic gases are generated, typically hydrogen at the cathode.

The current flow in the electrocoagulation cell is maintained by the flow of electrons resulting from the driving force of the electrical source. The solution electrolyte allows the current to flow by the motion of its ionic charged species. High conductivity is an advantage for the process, since it reduces the electrical resistance of the solution and the electrical consumption

Electrocoagulation process contains major reactions [29]:

1. Electrolytic reactions at the electrode
2. Formation of coagulants
3. Adsorption of pollutants
4. Removal of colloids by sedimentation or floatation

III. REACTIONS AT THE ELECTRODES

A simple electrocoagulation reactor is made up of one anode and one cathode (Figure 2). When a potential is applied from an external power source, the anode material undergoes oxidation, while the cathode will be subjected to reduction or reductive deposition of elemental metals. The electrochemical reactions with metal M as anode may be summarized as follows:

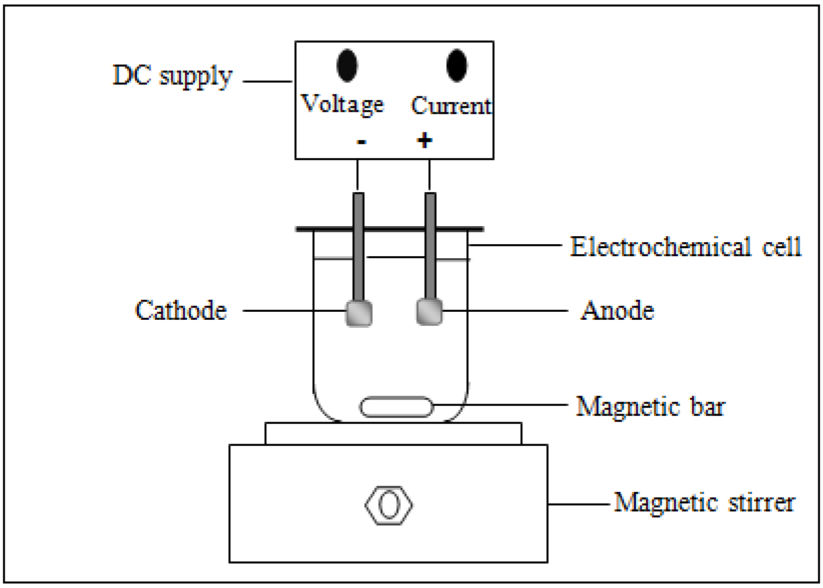

Figure 2: Simplified experimental setup of an electrocoagulation cell.

The main plate electrodes that are commonly used for electrocoagulation process are iron and aluminum, science these two materials have been extensively used to clarify wastewater [30]. The type of coagulant produced was determined according to the electrode materials used. This coagulant effects on the coagulation and the efficiency processes [31].

The main reactions take place at the metal electrodes [30][31]

Anodic reactions

Iron Electrode

Anode: $Fe \rightarrow Fe^{2+} + 2e$ (1)

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

Overall: $Fe^{2+} + 2H_2O \rightarrow H_2 + Fe(OH)_2$ (3)

OR

Anode: $Fe \rightarrow Fe^{3+} + 3e$ (4)

Cathode: $3H_2O + 3e \rightarrow \frac{3}{2}H_2 + 3OH^-$(5)

Overall: $Fe^{3+} + 3H_2O \rightarrow \frac{3}{2}H_2 + Fe(OH)_3$(6)

Aluminum Electrode

Anode: $Al \rightarrow Al^{3+} + 3e$ (7)

Cathode: $3H_2O + 3e \rightarrow \frac{3}{2}H_2 + 3OH^-$(8)

Overall: $Al^{3+} + 3H_2O \rightarrow \frac{3}{2}H_2 + Al(OH)\ 3$ (9)

In general:

Anode: $M \rightarrow Mn^+ + ne$ (10)

Cathode : $2H_2O + 2e \rightarrow H_2 + 2OH$(11)

Overall : $Mn^+ + nH_2O \rightarrow nH^+ + M(OH)_n$(12)

If we consider that the only chemical reactions occurring in the reactor electrocoagulation are metal oxidation at the anode and reduction of water at the cathode. It is possible to determine the mass of dissolved metal and hydrogen gas formed during a time t a current electrolysis I, using Faraday's law:

$$m_{theo} = \frac{I.t.M}{n.F} \qquad (13)$$

Where:

m: mass of dissolved metal or gas formed (g). ,I : current intensity (A). ,M: molar mass of the studied metal (g.mol-1). ,F : the Faraday constant (96500 Cb.mol-1). ,N : number of electrons involved in the reaction. ,t : electrolysis time (s).

Faraday s laws of electrolysis provide a theoretical estimate of the amount of Fe^{2+} and Al^{3+} ions dissolved from the anodes. They relates the current passed, I to the mass, m
The energy consumed (in kWh.m-3) is given by the following equation:

$$E = \frac{U.I.t}{V} \quad (14)$$

Where,
U : is cell voltage (V)., I : is the intensity (A)., t : is the time (h)., V : is the volume (m3). Equation (14) includes the energy of the anode dissolution and energy gas evolution. The percent of discoloration was calculated by the equation:

$$\text{Abatement}(\%) = \frac{C_o - C_{ap}}{C_o} * 100(15)$$

Where
C_0: initial solution concentration in mg/l. ,Cap: Concentration after treatment in mg/l.
The Faraday efficiency is calculated as follows:

$$\emptyset_c = \frac{\Delta m_{exp}}{\Delta m_{theo}}(16)$$

Where:
_m_{exp}: Experimental Mass of anode dissolved (g).,_m_{theo}: Theoretical Mass of aluminum released from the anode (g)
The electrode consumption is calculated as followed:

$$\mu_{Al} = \frac{\text{Massofaluminum}}{\text{Massofdey}} \qquad (17)$$

In an EC experiment, the electrode or electrode assembly is usually connected to an external DC source. The amount of metal dissolved or deposited is dependent on the quantity of electricity passed through the electrolytic solution. A simple relationship between current density (A cm^{-2}) and the amount of substances (M) dissolved (g of Mcm^{-2}) can be derived from Faraday's law:
w = itMnF(18)
Where w is the quantity of electrode material dissolved (g of Mcm^{-2}), ithe current density (A cm^{-2}), t the time in s; M the relative molar mass of the electrode concerned, nthe number of electrons in oxidation/reduction reaction, F the Faraday's constant, 96,500 C mol^{-1}.

IV. PARAMETERS AFFECTED ON ELECTROCOAGULATION

4.1 Effect of pH:

It has been established that the initial pH of solution is one of the important factors affecting the performance of electrochemical processes as pointed by several authors[32-39].

Currently, it has been established that the pH is a critical operating parameter influencing the performance of electrocoagulation process

Most pollutants in textile wastewater are weak organics acid or base, so the pH value of wastewater can influence the property of pollutants available in wastewater. The effect of pH in the range of 4 to 11 for treatment of textile industrial wastewater was carried out by using either H2SO4 or NaOH to adjust the pH of the solution.[40-42].

pH of the medium changes during the process, depending on the type of electrode material and initial pH. On the other hand, the electrocoagulation process exhibits some buffering capacity, especially in alkaline medium, which prevents large changes in pH and a decrease of the pollutant removal efficiency [43]. In acidic media, higher removal efficiencies are obtained. During the electrolysis, the pH of the medium increased, probably due to the liberation of H_2 (g) at the cathode and the formation of OH^- (aq) Ions. Hence, at higher initial pH, different metal hydroxide M $(OH)_n$ forms were present during the electrolytic process. For example: between pH 5 and 6, the dominant aluminum species are Al $(OH)^{2+}$ and $Al(OH)_3$, which acts as a coagulating agent. At pH 7, the removal efficiency of this contaminant was lower due to the formation of soluble [Al $(OH)^{4-}$] aluminum complexes caused an increase in pollutant removal.

The pH of the reaction solution changes during the EC process, and the final pH of the effluent actually affect the overall treatment performance. It is generally found that the aluminum

current efficiencies are higher at either acidic or alkaline conditions than at neutral. Initial pH of the solution is an important operating factor influencing performance of the EC process. However, the effluent pH after electro-coagulation treatment was found to increase. The increase of pH at acidic condition was attributed to hydrogen evolution and the generation of OH- ions at the cathodes [44].

As with aluminum and iron, other metal cations can also form hydroxides in water. Most non-ionic hydroxides have low solubility in water and can be removed by precipitation and co-precipitation with EC systems. Hanay and Hasar [45] studied removal of Cu(II), Mn(II) and Zn(II) by aluminum electrodes. Removal efficiency increased when initial pH of the wastewater increased. Similar results have been obtained for the removal of Co(II) [46], As(V), Cu, Cr and Ni [47], Cu(II), Pb(II) and Cd(II) [48], Cu(II), Ni(II), Zn(II) and Mn(II) [49], In(III) [50, Mn(II) [51] and Cr(III) [52]. Hg (II) removal was not significantly affected by initial pH in the range of 3–7 [53].

It has been established in previous studies that initial pH has a considerable effect on the efficiency of the electrocoagulation process for removal of organic pollutants [54][55].

Also, as pH increases the dissolved iron weight during the electrocoagulation process increases due to the formation of iron hydroxide species which absorb the dye molecules and causes the increase of the removal efficiency. The effect of pH on the process performance is explained as follows: the dominant iron species are different according to the solution pH; at basic pH, dye removal efficiency is increased as concentration of OH- ion increases which help in formation of different iron hydroxide complexes [56-58]

The adsorption rate of dyes by those species is lower than precipitation at lower pH because of the protonated functional groups of dye molecules. At higher initial pH, deprotonated functional groups of dyes enable adsorption of dyes on Al (OH)(n)(s) and aluminum hydroxyl complexes. Hence dye removal by precipitation is easier at lower pH while both adsorption and precipitation occur at higher pH [59].

4.2 Effect of Current Density

One of the most critical operation parameters in EC having integral effect on process efficiency as the current density**.** The effect of current density is another important parameter for pollutant removal in the electrocoagulation process that effects the metal hydroxide concentration formed during the process. High current density especially causes both decomposition of the electrode material [60].

With the increase of the current density higher values of removal efficiencies were obtained. The higher removal efficiency of contaminants with increased current density was due to the higher amount of ions produced on the electrodes that promote destabilization of the pollutant molecules and, finally, the aggregation of the induced flocs, while increasing hydrogen evolution. However, the increase of the current density causes higher consumption of the anode material [61].

Generally, an increase in current density causes the anodic oxidation to take place more readily, which in turn favors the formation of amorphous metal hydroxides species adequately in the vicinity of the electrode as well as in the bulk [62]. Current density not only influences coagulant dosage but also bubble formation rate, their size and the flocs growth [63].

Current density is one of the important factor influence the electrocoagulation process. it is found that, the removal efficiency of TS, COD and FC are increased rapidly up to current density of 20 mA/cm^2. This is explained the fact that, the coagulant production on the anode and cathode increases while increase the current density. Therefore, there is an increase in metal hydroxide (M (OH)$_3$) flocks formation in the reactor and hence the improvement in the removal efficiencies But, at higher current density (25–30 mA/cm^2), the removal of TS, COD and FC are almost constant [64]. Similar results were also noticed for treatment of paper mill bleaching wastewater using EC process [65-68].

4.3 Effect of Electrode Material

The selection of electrode material is important. The most common electrode materials for EC are aluminum and iron. They are cheap, readily, available and effective [69-70].

Metal electrodes are dissolved during the EC process, which occurs with coagulant species and metal hydroxides Metal anode dissolution is accompanied by hydrogen gas evolution at cathodes, the bubbles capturing and floating the suspended solids formed and thus removing contaminants [71-72].

Electrode material defines which electrochemical reactions take place in the EC system. Aluminum and iron electrodes have both been used successfully in EC systems. Aluminum dissolves in all cases as Al (III) whereas there is some controversy as to whether iron dissolves as Fe (II) or Fe (III) [73-74]. Most results indicate that iron dissolves as Fe(II), such as [75][76], and is oxidized in bulk solution to Fe(III) if there are oxidants, such as oxygen, present in sufficient concentration and pH is alkaline .. Fe (II) is a poor coagulant compared to Fe(III) due to higher solubility of hydroxides and lower positive charge, which explains some poor results obtained with iron electrodes, such as in the study of Bagga et al. [76]. Optimal material selection depends on the pollutants to be removed and the chemical properties of the electrolyte. In general, aluminum seems to be superior compared to iron in most cases when only the efficiency of the treatment is considered. However, it should be noted that aluminum is more expensive than iron [77].

Linares-Hernández et al. [75] obtained high removal of color with aluminum electrodes, while iron was more effective than aluminum in reducing COD from industrial wastewater. A combination of iron and aluminum removes both color (71%) and COD (69%) with high efficiency. Similar results were obtained when paper mill wastewaters were treated with various aluminum and iron electrode combinations [78].

Aluminum electrodes were most effective in removing color of the wastewater, whereas iron electrodes removed COD and phenol from the wastewater more effectively than aluminum electrodes. A combination of aluminum and iron electrodes removed color, COD and phenol with high efficiency.

Combination electrodes have been studied for arsenic removal from groundwater [79]. Iron electrodes and a combination of iron and aluminum electrodes gave the highest arsenic removal efficiencies. Similar results were obtained for copper, chromium and nickel removal from metal plating wastewater [80]. Fe-Al pair has been most effective in removing indium from water [81].

4.4 Effect of Electrolyte (NaCl) Concentration

It is important to investigate the effect of electrolyte concentration since actual wastewater usually contains certain amount of salts as the electrolyte concentration increased, the removal efficiency increased due to the increment of the electrical conductivity reaching the maximum value. However, with the increase in NaCl concentration, the removal efficiency decreased

It can be attributed that at a constant voltage with increasing of electrolyte concentration, conductivity of dye solution increases and resistance decreases, so the passed current increases and the produced amount of metallic hydroxide and dye removal increases [82].

Sodium chloride is usually employed to increase the conductivity of the water or wastewater to be treated. The effect of electrolyte type on the removal efficiency using Fe and Al electrodes respectively in the presence of different supporting electrolytes including NaCl, KCl, CaCl2, NaF, Na2CO3, Na_3PO_4 were studied. Experiments were done using NaCl because it is cheap and the solution contains it has high conductivity thus it need low voltage for electrocoagulation and so it is economical in industrial scale.

Generally, NaCl was used as supporting electrolyte in electrochemical process. NaCl was chosen as supporting electrolyte due to its capability to enhance the degradation efficiency and shortened the reaction times [83, 84].

It is apparent that increasing the chloride concentration may increases the COD removal due to the increased mass transport of chloride ions to the anode surface and also increased diffusion in the diffusion layer of the anode (Figure 2). As a result, more amount of hypochlorite ion will be generated .Thus; higher concentrations of hypochlorite ion were able to oxidize more organic molecules in wastewater [85]. 0.1 M of NaCl was considered as an optimum electrolyte concentration due to highest COD removal in textile industrial wastewater.

Solution conductivity affects the current efficiency, cell voltage and consumption of electrical energy in electrolytic cells. Typically, KCl is used to obtain the conductivity in EC process.

4.5 Effect of EC Time

The EC time is another significant parameter that is influential on the electrocoagulation process. Because the formation and concentrations of metal hydroxides play an important role on pollutant (COD, turbidity and phosphorus) removal, this depends on operation time

Reaction time is one of the most important operational parameters for all electrochemical treatment processes as with the increase of reaction time, corrosion of electrodes releases higher amounts of coagulant ions in the solution, an increase in reaction time improved the efficiency of phosphate removal [86].Increase in electrolysis time leads to an increase in coagulant concentrations that has been reported to reduce the floc density, then to reduce their settling velocity [87].This is due to the fact that with an increase in the electrolysis time, more ions will be dissolved in the wastewater leading to an increase in flocs formation [88].

Electrolysis time is of vital importance in the performance EC process. it is found that, removal of efficiency of TS, COD and FC increases with increasing electrolysis time up to 15 min, thereafter removal efficiency shows almost constant. It can be explained by the fact that electrolysis time increases, an increase occurs in the amount of metal hydroxide flocs ($M(OH)_3$) which promotes the removal of TS, COD and FC via a sweep coagulation followed by precipitation mechanism, thus removal efficiency of TS, COD and FC increased. Thereafter (15–30 min), almost all toxic matters are removed as flocs and hence no change in removal of TS, COD and FC removal with the increase in electrolysis time [89].

The COD removal efficiency depends directly on the concentration of electrochemical generated hypochlorite ion in the bulk solution. When the electrolysis time was longer, more hypochlorite ion will be produced in solution under fixed current density. Therefore, color and COD value in the solution were reduced in higher concentration of hypochlorite

Preliminary settling process is a natural treatment method that requires no chemical addition. Although some workers realized the importance of the natural settling process, there is little information available in the literature on the effect of the preliminary settling time on pollutants removal capacity [90]. That removal efficiency increased with settling time

The sharp increase in removal efficiency with time at the early stage of settling is in accordance with the theory of rapid coagulation proposed by Smoluchowski et al. [91].

4.6 Electrical Energy and Electrode Consumption.

Electrical energy consumption is a very important economical parameter in the electrocoagulation process. It can be seen that the longer contact time of the system applied, the weight of the electrode consumed in the simple EC process has been increased The variation of electrical energy consumption increased proportionally with contact time [92]

4.7 Effect of Applied Voltage

In all electrochemical processes applied voltage is the most important parameter for controlling the reaction rate within the electrochemical reactor [93].It is well known that this variable determines the production rate of coagulant, adjusts also bubble production, and hence affects the growth of formed flocs.

4.8 The Effect of Inter Electrode Distance

The distance between the electrodes is an important variable to optimize operating costs. The greater the inter electrode distance, the greater should be the difference in applied potential, because the solution presents higher resistivity to the electrical current. According to the characteristics of the effluent, the process efficiency can be improved by varying the distance between the electrodes [94]

This is an important variable with regards to operational costs. In the case of high values of the conductivity of the effluent, it is recommended that, when the conductivity of the effluent is relatively high, greater inter electrode distance be used. In the case of moderate values, it is recommended to use a smaller distance, as this will reduce the energy consumption. When the inter electrode distance increases, the removal efficiencies also increase. This change probably occurs due to electrostatic effects, since they depend upon this distance; when it increases, the ion movement is slower and there would be greater opportunity to generate aggregate flakes. Moreover, these flakes are able to adsorb more molecules [95]

Increasing the electrode spacing will reduce the capital cost of treatment but may reduce the treatment efficiency. However, with increasing the distance, the removal efficiency decreased. It can be attributed that with increasing of distance between electrodes at constant voltage, electrical resistance between electrodes increases and current passed through electrodes decreases. The decreasing of current, lead to lower production of hydroxyl ions and dye removal efficiency decreases [96].

It is observed that, removal efficiency of TS, COD and FC are increased with the increasing electrode distance up to 5 cm. At minimum inter electrode distance the resistance for current flow in the reactor is lower that facilitates the EC process for enhanced removal of TS, COD and FC. But, beyond 5 cm of electrode distance shows the decrease in removal efficiency of TS, COD and FC. This is due to the formation of ohmic loses which in turn inhibits the production of M (OH)3 flocs, thus the removal of TS, COD and FC gets decreased. As the distance between the two electrodes decreased, the removal efficiency increased due to the increment of the electrical conductivity reaching.

The greater the inter electrode distance, the greater should be the difference in applied potential, because the solution presents higher resistivity to the electrical current. According to the characteristics of the effluent, the process efficiency can be improved by varying the distance between the electrodes [97]

4.9 Effect of Operating Temperature:

Temperature is another important operating condition that can affect pollutant removal efficiency in wastewater treatment generally. The efficiency of turbidity removal from abattoir wastewater in the EC process increased by increasing solution temperature

The increase in removal efficiency with temperature in the EC process can be explained by the fact that increasing solution temperature can improve ion transfer from the anode and/or cathode surface to the solution bulk resulting in a decrease in solution viscosity and consequent increase in the ion diffusivity.

The effect of temperature on the removal of pollutants through EC has been studied in a few articles. The effect of solution temperature on boron removal by EC has been studied in the range of 293–333 K [98-100].

Removal efficiency was 29% lower at 293 K than in higher temperatures. Authors concluded that at low temperatures the dissolution of anode occurs at a lower rate. However, they did not present any results, such as concentrations of aluminum dissolved from electrodes, which would support this conclusion. It has been suggested that when temperature is too high, there is shrinkage of large pores of the $Al(OH)_3$ gel, which causes the formation of dense flocs that are more likely to deposit on the electrode surface [101]. Increasing temperature also enhances the solubility of aluminum. However, it seems that increasing temperature can have positive and negative effects on the removal efficiency. It is possible that the effect of temperature on removal efficiency depends on the removal mechanism of pollutants.

The results indicate that increasing temperature has a negative effect on removal.However, it should be noted that the operation of electrocoagulation process at higher temperature significantly reduced electrical energy consumption and fluid conductivity increases. So, the production of hydroxide species increases rapidly then enhances pH value. The increase in pH may be affecting on iron and aluminum species to be in the oxide form and did not exist in the hydroxide form which is the coagulant species that should remove the dye.

4.10 Effect of Initial Dye Concentration

Results showed that when dye concentration increased ,removals efficiencies decreased. One of the most important pathways of dye removal by electrocoagulation is adsorption of dye molecules on metallic hydroxide flocs. The adsorption capacity of flocs is limited and specific amount of flocs is able to adsorb specific amount of dye molecules. So, with increasing of dye concentration, amount of produced flocs is insufficient to adsorb all dye molecules, therefore dye and COD removal decreases.

V. ELECTRICAL POWER CONSUMPTION FOR THE EC PROCESS

The electric power consumption of the process was calculated per m^3 of the effluent solution using equation 19

$$P=EIt/V \qquad (19)$$

Where

P is the specific power consumption (W.h/m3). E is the cell voltage in volt (V). I is the current in ampere (A), t is the time of electrocoagulation in hour (h) and V is the solution volume in cubic meter (m3).

It is clear that increasing the current intensity will increase power consumption.

The increase in power consumption can be ascribed to the increased polarization on the two electrodes by increasing the current intensity [102]

VI. MASS OF THE ELECTRODES DISSOLVED DURING THE ELECTROCOAGULATION PROCESS

The theoretically maximum dissolved mass of iron that occur during electrocoagulation process from the sacrificial anode for a specific electrical current flow in an electrolytic cell was calculated using equation 20.[103]

$$M=I.t.Mr/z.F \qquad (20)$$

M is the amount of the dissolved anode material (g); I is the current (A); t is the electrolysis time (s); Mr is the specific molecular weight of the anode electrode (Fe). The anodic dissolution of iron led to the species Fe^{2+} (and thus z for iron is 2), this species oxidizes rapidly in air to Fe (III) which has significant coagulation properties [104].

VII. ADVANTAGES AND DISADVANTAGES OF EC PROCESS

7.1 Advantages-

1. Ec process is easy in operate
2. Ec process needs a simple equipment
3. It is no need chemicals
4. Ec process requires less maintenance
5. The process requires less civil works and other constructions
6. Sludge formed by EC process is readily settable and easy de-watered
7. Flocs formed by EC process tends to be much larger
8. The gas bubbles generated at the time of electrolysis can be separated easily
9. An alternative renewable sources energy such as solar and wind energy can be used instead of electrical source.
10. EC process is used to removes the smallest colloidal particles
11. Ec process give clear , colorless and odorless water[105-110]

7.2 Disadvantages

1. The sacrificial anodes need to be replaced periodically
2. The use of electricity may be expensive in some cases
3. High conductivity of the wastewater suspension is required
4. The high cost of electricity can result in an increase in operational
5. The hydrogen gas produced could be explosive unless it is collected safely.
6. Gelatinous hydroxide may tend to solubilize in some cases **[**111-113**].**

Table 1Reviews the removal of pollutants by electrocoagulation method for a period between 2010 to 2018

Table 1
Summary of pollutants removed by electrocoagulation method

Type of wastewater	Removal parameter	Anode-Cathode	Current density (A/m^2), Current (or Voltage)	Time(min)	pH	Max removal efficiency (%)	References
Synthetic dye-water	Direct black 22, Acid red 97, COD	Fe-Fe , Al-Al	50-100	5-15	8	91.76 91.0 62.5	[114]
Oil-water	Palm oil COD SS TDS	Al-Al	20-60	5-15	5	72 64 53 43	[115]
Nitrate-water	Cr(VI)	Fe-Fe, Al-Al	(10-20 V)	12-60	7	89.7	[116]
Domestic wastewater	COD Turbidity phosphorus	Fe-Fe, Al-Al	10-150	5-40	7.8	72 98 98	[117]
Textile wastewater	COD Dyestuff	Fe hexagonal wire	200	90	7	93 93	[118]
Textile wastewater	4 Synthetic dyes	Al-Al	251.6	60	6.5-9.7	87-97	[119]
Textile wastewater	Orange II dye	Fe-Fe	(30 V)	30	7.5-10	60-92	[120]
Domestic wastewater	COD TDS	Fe-Fe	(0.12-0.36 A)	5-20	6.7	90 90	[121]
Synthetic wastewater	polyphosphate	steel	11.5	60	7.2	99.85	[122]
Synthetic wastewater	AMP SHMP	steel	1.15	60	7-7.5	98.72 100	[123]
Dairy wastewater	COD BOD TSS	Al-Al	(10- 60V) (0-5 A)	15-60	7.2	98.84 97.95 97.75	[124]
Textile wastewater	MB dye	Fe-Fe	80	10-20	12	80	[125]
Textile wastewater	Azo dye (RY- 14)	Fe-Fe	(10-40 V)	10-25	2	99.27	[126]
Textile wastewater	RS dye	Fe-Fe	100-300	0-90	7.1	96.5	[127]
Textile wastewater	COD Turbidity	Fe-Fe	50-125	0-60	5-7	79.86 96.88	[128]
Hospital wastewater	COD	Fe-Fe Al-Al	(10-30 V)	30-60	3-11	87.1	[129]
Textile wastewater	BR-18 dye	Al-Al	(10-60 V) (0-5 A)	10-60	3-11	97.7	[130]
Dying wastewater	R R195 dye	Fe-Fe	(2-5 A)	0-30	3-12	99.1	[131]
Textile wastewater	BR dye 5001B COD	Fe-Fe	140-170	0-60	9	76 95	[132]
Textile wastewater	RG- 19 dye	Al-Al	(10-50 V)	10-60	3-11	99.88	[133]
Synthetic wastewater	polyphosphate	Steel	0.6	0-60	7.2	85-99.85	[134]
Textile wastewater	MB dye	Fe-Fe Al-Al	10-50	2-24	3-9	100 95.78	[135]
Dying wastewater	Azo-2-naphthol dye	Al-Al	(0.3-24 V)	0-120	7.0	90	[136]
Dying wastewater	Crystal Violet dye Organic mattar	Al-SS	150-250	10-60	3.5-5.5	99 98	[137]
Sewage wastewater	TSS, TDS, COD	Fe-Fe	50-650	0-40	5-12	----------	[138]
Oily wastewater	COD Diesel	Fe-Fe Al-Al	(4.5-10.5 V)	10-60	3-11	99.1 98.8	[139]
Synthetic wastewater	RR 141 dye	Fe-Fe	50-300	3-30	4-12	99.88	[140]
Synthetic	Nitrate	Al-Al	60-140	10-90	7-11	91	[141]

wastewater							
Textile wastewater	Color Turbidity	Fe-Fe Al-Al	0-100	0-55	2.3-8.8	90 97	[142]
Textile wastewater	Malachite green dye COD	SS-SS	(15 V)	10-30	4-10	99.5 85.71	[143]
Textile wastewater	Reactive red 24 dye COD	Fe-Fe Al-Al	50-200	5-35	1.8-10	99.6, 91.5 97.9, 83.8	[144]
Textile wastewater	Reactive violet 5 dye	Al-SS Fe-SS SS-SS	100-250	0-15	5.8	22 91.5 99.8	[145]
Aqueous solution	Brilliant green dye	Fe-Fe	13.9-138.9	0-30	1.5-10	99.59	[146]
Textile wastewater	Azo RR-29 dye Azo DB79 dye	SS-SS	15.7-35.0 15.7-40	0-60	4-8	98.6 90.4	[147]
Dairy wastewater	Conductivity Turbidity	Al-Al	(5-25 V)	15-75	6-8	93 94	[148]
Contaminated water	Malachite green dye	Al-Al Fe-Fe	20-120	0-30	2-12	99	[149]
Textile wastewater	Acid black 194 dye	Fe-Fe	5-100	0-60	4-8.5	Over 75	[150]
Paint industry wastewater	COD	Al-Al	(0-20V)	10-40	3-10	73.3 1	[151]
Oily wastewater	Oil & Grease Suspended Solids SS	Fe-Fe Al-Al	20-200	10-70	8-8.5 6-6.5	59 100	[152]

VIII. CONCLUSIONS

The main point of this review article was focused on the electrocoagulation method used to treat water and wastewaters by studying the mechanism, chemical reactions on the electrodes and the effect parameters. It was found that electrocoagulation technique is an effective treatment technique for the removal of wastes from water. It has been noted that electrocoagulation is capable of having high removal efficiencies as compared with other treatment techniques. Electrocoagulation is an attractive method for the treatment of various kinds of wastewater. The process is characterized by simple equipment, easy operation, less operating time and decreased amount of sludge which sediments rapidly. In this review article, it is scanned research articles applied electrocoagulation process from a period of 2010 to 2018. As a result, this technology has excellent future because of numerous advantages was found when used this technique.

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