Al-Khwarizmi Engineering Journal
ISSN (printed): 1818 – 1171, ISSN (online): 2312 – 0789
Vol. 20, No. 1, March, (2024), P P. 17- 32

Al-Khwarizmi Engineering Journal

Factors Affecting Electrocoagulation Process for Different Water Types: A review

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(Received 29 April 2023; Accepted 16 October 2023; Published 1 March 2024)
https://doi.org/10.22153/kej.2024.10.001

Abstract

Raw water must meet specific physical, chemical, and biological requirements to be suitable for drinking. There are various techniques available for treating wastewater, and aside from conventional methods that involve chemicals, electrocoagulation is an efficient and advanced approach. Electrocoagulation has proven effective in treating many pollutants, including bacteria, viruses, iron, fluoride, sulfate, boron, hardness, and turbidity. Total suspended solids, organic and inorganic materials, chemical oxygen demand COD, biochemical oxygen demand BOD, and color. It finds extensive application in treating different types of water and wastewater due to its exceptional ability to remove diverse contaminants. Recently, electrocoagulation has garnered significant attention due to its remarkable efficiency in treating various pollutants. This article provides a thorough analysis of contemporary literature that is committed to using electrocoagulation in a variety of water treatment methods, with a focus on the different variables affecting the process performance, such as electrical current, electrode type, electrode configuration, initial pH, electrode distance, NaCl concentration, initial concentration of pollutants, operating temperature and electrolysis time.

Keywords: *Electrocoagulation, sulfate, iron, aluminum, anode, and cathode.*

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1. Introduction

One of a person's basic requirements is water, which is also a key component of any area's evolution. Excess use of pesticides, herbicides, and fertilizers, leaky fuel and chemical tanks, chemical spills in industry, drainage of domestic chemical products,improperly managed landfills (groundwater assessment and its electrochemical treatment), suspended solids, biodegraded organic compounds, pathogens, nutrients, organic materials that are refractory, silica, heavy metals, and Natural organic material NOM are just a few examples of human activities that cause water pollution. Direct sewage discharge into natural water bodies without treatment is not encouraged since the organic waste's degradation would significantly affect water quality. Additionally, harmful microbes can spread infectious diseases. When nutrients like nitrogen and phosphorus, together with organic matter, are released into an aquatic environment, it can also promote the development of undesired aquatic life. When these nutrients are discharged excessively on land, it can also cause groundwater contamination [1]. Using electricity to purify water was originally used in the UK in 1889 [2]. In 1946, the United States used electrocoagulation on a broad scale for the first time. Due to its adaptability and low environmental impact, the electrocoagulation technique has garnered much interest in treating water [3] [4].

Electrocoagulation, a treatment that is effective, economical, and favorable to the environment, has received much attention lately. Its unique features are its ease of use, minimal sludge generation, lack of extra chemical requirements, and effectiveness of the electrocoagulation process in removing toxins from water and wastewater. For removing pollutants, up to 99% removal efficiency has been observed usingelectrocoagulation [5]. Electrocoagulation has shown to be quite efficient at removing various impurities from drinkingwater [6].

By substituting electrocoagulation for traditional chemical dosing, which involves adding primary coagulants such as ferric chloride or ferric sulphate, alum, Aluminum chlorohydrate (ACH), polyaluminum chloride (PAC), or aluminum as the inorganic metal salt, settling is used to remove pollutants [7].

2. Electrocoagulation Process

2.1 Principles of Electrocoagulation (EC) Process Method

Destabilizing dissolved, emulsified, or suspended pollutants in an aqueous media isdone using electrocoagulation [8][5]. It combines chemical and physical treatments. It is an electrochemical process that uses the fundamental principles of conventional water treatment. In opposition to the coagulation technique, which involves adding coagulant particles to the pollutant to combine it, electrocoagulation employs electrodes to discharge the coagulant [9].

It has been successfully tested for cleaning municipal wastewater, textile wastewater, drinking water, poultry manure, landfill leachate oily water, and river and groundwater. This process is distinguished by its uncomplicated operation, simple equipment, lower reactive retention time, lack of equipment for chemical addition, and decreased sludge or precipitate levels that settle quickly [3]. Electrochemical scale removal has various benefits, including environmental protection, eliminating the need to handle and administer chemicals, automation accessibility, and practical process management [10]. The biggest challenge is getting rid of the precipitated scale [11]. The ability to fully automate the process, a small treatment facility, cheap cost, and great particle removal efficiency. Reduced sludge output, minimal chemical requirements, and simplicity of operation [12]. Higher removal efficiency and a wider range of pollutants can be removed from an electrocoagulation unit than from a chemical coagulation due to the numerous processes that take place there [6] [8].

Alum and ferric chloride are examples of common chemical coagulants that add counterions to the solution in addition to the metal cations that serve as the coagulant. Compared to electrocoagulation, chemical coagulation necessitates handling more material. Acid is produced substantially less by the electrochemical precipitation of iron or aluminum hydroxide than by chemical coagulation. On the contrary, creating these precipitates by electrocoagulation does not add any acid to the solution [13].

Since electrocoagulation mostly comprises metallic oxides and hydroxides, it requires basic equipment, produces little sludge, and is very simple to dewater. Chemical flocs are comparable to electrocoagulation flocs; However, electrocoagulation flocs are more stable, larger, and contain less bound water. As a result, settling and filtering can separate them more quickly. No more chemicals are utilized since the technique prevents their use. Maintenance is minimal because the electrocoagulation process has no moving elements and is electrically controlled. In rural locations without access to power, it can also be used with solar energy. The disadvantages of electrocoagulation include the need to replace electrodes regularly because they dissolve, the high cost of power and anode passivation, and gelatinous hydroxides, which in certain situations tend to solubilize [5].

The electrocoagulation process has the following advantages over other chemical processes: compared to other chemical procedures, effluent has fewer total dissolved solids, is easy to operate, and degrades organic waste more quickly and effectively than chemical coagulation; Compared to those produced by chemical coagulation, bigger and more stable flocs are developed; Except in severe circumstances, controlling the pH of the water does not need the use of chemicals, lowers residue, it processes a variety of contaminants that are simple to remove, and its operating costs are far lower than those of most current technologies, The device may be utilized as a decentralized process since it is simpler and smaller than the coagulation device, and if solar panels are applied, In remote regions without access to power, the device canbe utilized as a batch process to handle lesser amounts of waste water few of the drawbacks of electrocoagulation include the possibility of high power costs in some locations, the possibility of anode passivation related to oxygen present, and cathode deposition (can be overcome by changing the electrode poles), Since the electrodes must be replaced frequently, raising maintenance expenses, high wastewater conductivity isnecessary. It's necessary to eliminate the effluent's high quantities of iron and aluminum. While the gelatinous hydroxides may occasionally be dissolved in water, this method is ineffective for removing soluble materials, including solvents, organic acids, sugars, phenols, alcohol, and related compounds [14].

2.2 Mechanisms of EC method

The electrocoagulation technique can generate coagulants on-site by electrochemically dissolving Fe or Al electrodes in an electrolyte solution to destabilize contaminants [15].

In the EC cell, as the electric current supplied to the electrochemical cell, the anode dissolves and produces metal cations [15].

During the procedure, current is transferred between electrodes and through an aqueous solution, producing metal ions on the site [6].

An applied voltage creates the coagulant species in situ as the sacrificial metal anode (aluminum or iron) dissolves [16][17]. Since the sacrificial anodes corrode when an applied voltage is provided, electrocoagulation delivers the coagulants in place (Lin al., n.d.).

As the isoelectric point is reached, aluminum cations first help to neutralize the charge on the pollution particles. As with other charged polymeric metal hydroxide species, these cations can neutralize negatively charged particles. After being neutralized, aggregates or flocs may be created when the particles come together, which will remove the pollutants [5].

2.3 Theory of EC method

In Electrocoagulation (EC) for a continuous flow, the electrolytic gas produces a flotation action once the floc is produced, contaminants are removed from the floc-foam layer ; at the liquid's surface [3] (Kabdaşlı et al., 2012) loose in aggregatesare created as a result of the sorption coagulation action [16] (Holt et al., 2004).

It includes dissolving metal from the anode while producing hydroxyl ions, coagulant specie, that either precipitate and absorb dissolved contaminants or aggregate suspended particles [20][21] [22].

Electro flotation removes extra impurities not eliminated in chemical coagulation due to the development of gas bubbles at both electrodes. Like the coagulant salts employed in conventional chemical coagulation, such as alum and ferric chloride, the cations result from electrocoagulation, spontaneously forming polymeric metal hydroxide species in solution [5].

These metal ions combine to produce oxides and poly-oxyhydroxide complexes, which function as coagulants and can eliminate water pollutants. Coagulation, electro-oxidation, electro-flotation, precipitation, adsorption, and settling are the mechanisms for removing contaminants due to the several operations that run concurrently in a single unit [6]. Highly charged cations destabilize any colloidal particle by producing polyvalent polyhydroxide complexes. Due to their strong adsorption abilities, these complexes combine with contaminants to create aggregates [3]. In EC, As time passes, more aluminum cation addition causes the precipitation of amorphous aluminum hydroxide, which encourages pollutant aggregation [16].

Electrocoagulation involves a collision between negative OH ions and positive metal ions enhancing the creation of gelatinous hydroxide species. Due to its gelatinous nature, the hydroxide may stick to the electrode surface and develop into a film as the process goes on (Medhi, et al., 2008).

In addition to coagulation, flocculation, and settling, electroflotation occurs during electrocoagulation [5].

2.4 Chemical Reactions

An electrocoagulation reactor comprises an electrolytic cell with a single anode and a single cathode in its basic form. The "sacrificial electrodes," which are conductive metal plates, may be made of the same material (Anode and cathode). [5].

Metallic cations are produced in the anode and hydrogen in the cathode [9]. While the cathode evolves hydrogen to enable pollutant removal by flotation. The small gas bubbles also encourage mixing [9] [7] [23][16] [3]. When water is electrolyzed, tiny oxygen bubbles that are created collide with air bubbles, causing the pollution particles to float [24] [16]. Several methods exist for species interacting in a solution [3](Kabdaşlı et al., 2012).

First, switching to an electrode with the opposite charge (electrophoresis), followed by aggregation resulting from charge neutralization, the pollutant then forms a precipitate with the cation or hydroxyl ion OH^-. Bridge coagulation occurs when the metallic cation combines with OH^- to create a hydroxide with strong adsorption characteristics and bonds to the pollutant. These hydroxides sweep into the water and create bigger lattice-like structures, creating a sweep coagulation process pollution is then oxidized into less toxic particles. Lastly, electro-flotation and adhesion removal [3] (Kabdaşlı et al., 2012).

The cationic monomeric species are created by the electrolytic dissolution of the AL anode, as aluminum metal is used as the electrode. Species like AL^{+3} and $AL(OH)_2^+$. At acidic conditions. At appropriate pH values, they are transformed initially into $AL(OH)_3$ and finally polymerized to $AL_n(OH)_{3n}$ based on the following reactions. [27]

$Al \rightarrow Al^{3+}_{(aq)} + 3e^-$

$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al(OH)_3 + 3H^+_{(aq)}$

$nAl(OH)_3 \rightarrow Al_n(OH)_{3n}$

Colloid particles are made less stable by producing monomeric and polymeric hydroxides. Metal cations (Mn^+) destabilize colloidal particles, which encase colloidal particles in flocs that may be readily extracted from water through sedimentation or flotation. In equation 1, Metal from the anode is oxidized to its cations (Mn^+) when the current is transmitted through the electrode. Simultaneously, water is reduced to hydrogen gas, and the hydroxide ion (OH^-) will be formed on the cathode (equation 2) (Kabdaşlı et al., 2012) [14].

$M \rightarrow M^{n+} + ne^-$

$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-\ (aq)$

3. Factors Affecting Electrocoagulation

There are many factors affecting the electrocoagulation process, such as electrical current applied (voltage applied), the distance between electrodes, the configuration of the electrode, pH of the solution, ions concentration at the start of the process, the materials used in the process as an anode and cathode, the type of treated water, the conductivity of the solution, temperature, hydrolysis time, sodium chloride concentration.

3.1 Electrical current

The electrical current is one of the most efficient components in the electrochemicalprecipitation and electrocoagulation processes [28]. Increasing the electrode area and voltage and reducing the interelectrode distance are the three methods to enhance the current density [29]. According to Faraday's rule, the mass created by an electrode is inversely related to the quantity of electricity utilized. The amount of adsorbent (aluminum hydroxide) produced is directly proportional to the current density and depends on time. [30] [31]. Thus, As the adsorbent concentration rises, the amount of anode adsorption increases. This implies that adsorption depends on the anode's capacity to find binding sites [31].

Knowing the current density that can impact the efficacy of electrocoagulation allows one to calculate the coagulant dosage rate, the rate at which hydrogen bubbles are produced, the floc size, and the pace at which flocs expand. The distance between the electrodes, the conductivity of the solution, and the current intensity employed during the electrocoagulation process are all considered when determining the voltage. The conductivity of the solution is inversely related to resistance. There is a suitable value for current density depending on the processing load [30].

Also, Higher current densities for electrocoagulation may be accomplished by expanding the electrode area, reducing the interelectrode distance, and raising the voltage since the voltage determines the current density (Suryaningsih et al., 2021). The effectiveness of hardness reduction rises with an increase in electrical current. The size and growth rate of the created flocs increases at high voltages, impacting how well the process works for a pH value of 10 [32] [33]. Increased electrical potential results in a rise in the quantity of oxidize aluminum and, as a result, increases the number of hydroxide flocs with high adsorption rates, which improves the effectiveness of hardness removal [34] [35]. The density of bubbles on apposition rises, but their size falls as the electrical current increases. The effectiveness of flotation rose as density, and bubble size decreased because larger bubbles' effective surface and retention time were lower than those of smaller ones [36]. Naturally, surfactants are occasionally employed to reduce the surface tension of solutions and, as a result, the size of bubbles. Because when the electrical current decreases, more time is needed to achieve equivalent efficiency. These facts are consistent with the findings of studies conducted in 2004 by Ranta Kumar et al. regarding the removal of arsenic by the electrocoagulation method and in 2007 by Bzrafshan et al. regarding the effectiveness of the electrocoagulation method using aluminum electrodes in the removal of Cr^{+6} [34] [35]. Typically, 20 volts of electrical potential are needed to achieve noticeable efficiency. Electrode electrical conductivity indeed has an impact on efficiency as well. The electrical conductivity is directly correlated with the electrode distance. As the electrode's distance increases, more power is used, which increases the removal's efficiency [37] [32].

3.2 Electrode types

The choice of an electrode material depends on various elements, such as cost, low oxidation potential, compatibility with the system being utilized, etc. Different electrodes were reported in the literature like carbon [38], mild steel (Golder et al., 2005), iron [40], graphite titanium [41], titanium [42] and aluminum [43] According to reports, aluminum is quite effective and successful in removing pollutants under acceptable operating circumstances [16].

In the electrocoagulation reactor, while the direct current is delivered to them, untreated water flows between the anode and the cathode. Electrodes are usually made of iron (Fe) or aluminum (Al) because they are inexpensive, readily available, harmless, and effective. The electrode configurations and materials are chosen depending on the wastewater pollution and the standard of the desired effluent. Mostly iron is used to treat wastewater, while aluminum is used to treat drinking water [14]. The electrode material is widely recognized as a crucial element in electrocoagulation since it substantially impacts pollutant removal and energy consumption [14]. The electrode's chemical and physical characteristics impact the type of metal hydroxide and cations produced from the anode. Additionally, the electrode material used for water and wastewater treatment must be safe for both the environment and individuals [44]. Due to their multivalent ions' coagulation ability, aluminum and iron electrodes are commonly used in coagulation water treatment [45] [46].

3.3 Electrode Configuration

The electrocoagulation technique uses both monopolar and bipolar configurations. The anode and cathode are connected in parallel. In a parallel monopolar configuration, each couple of electrodes has a negative and positive charge. In a bipolar system, there is just one power connection and no electrical connection between the inner electrodes. Iron and aluminum electrode efficiency is higher in the bipolar system.

With a bipolar setup, organic matter may be reduced with an efficiency of 83%, while using a monopolar configuration, organic matter may be reduced by 71.1%. A flat electrode is less effective in removing pollutants than an electrode with holes (mesh). Electrodes with this hole have 1.2 times more capacity to increaseor release current than flat electrodes. [30]

Bipolar connections were shown to be more effective at removing organic compounds than monopolar connections when the efficacy of an electrocoagulation flotation method for water treatment was tested [47]. Due to its larger surface area, the bipolar connection may have a higher operating cost [16][48].

It is well recognized that current density (CD) not only determines the dose rate of the coagulant, but also the flocs' size, rate, and increment, all of which can affect how effectively the electrocoagulation works [49].

For the bipolar series system, as the current density grew, the removal of ions gradually increased for a certain amount of time before remaining mostly steady until the process was complete. Therefore, Anodic oxidation occurs more quickly inboth systems when the current density is increased, which helps with the proper arrangement of amorphous aluminum hydroxide species inside the anode and within the bulk [16]. A greater surface area than that of monopolar parallel in the electrocoagulation system with bipolar series preferentially the anodic oxidation. Due to the higher intensity of the bipolar connection compared to the otherkind, the removal efficiency of the ions is similarly higher than that of the monopolarconnection for the same amount of current density [50] (Anwer & Majeed, 2020).

3.4 Initial pH

It has been determined that pH is one of the key parameters influencing the effectiveness of the electrochemical process. As the process is mainly depends on the pH of the electrolyte at the start of the experiment.

Numerous studies found that removal efficiency declined at higher alkaline and acidic pH values. [52] and was ascribed to the amphoteric behavior of $AL(OH)_3$, which produces monomeric anions $AL(OH)^{-4}$ (at alkaline pH) and soluble AL^{+3} cations (at acidic pH). These soluble species are known to be worthless for treating water. The aluminum generated at the anode formed polymeric species when the initial pH was neutral. ($AL_{13}O_4$ $(OH)_{24}{}^{7+}$)and precipitated $AL(OH)_{3,}$ resulting in greater removal efficiency [53].

Due to the increasing amount of iron dissolution, the turbidity removal efficiency for all retention durations was usually improved when the current density was raised. It should be noted that as the hydraulic retention periods investigated in one specific study were at least two orders of magnitude longer than the particle migration time, it is not believed to be a significant influence that the increased particle migration toward anodic surfaces brought on by the greater electrical field at a higher applied current [54].

In Vasudevan research, at pH 12 (alkaline medium), the anionic phosphate in the solution would prefer to be repelled by the oxide surface due to its net negative charge, resulting in a minimum removal effectiveness of phosphate of 50%. However, pH 7 had the greatest quantity of phosphate removal [8], the same outcome, where the net negative charge of the oxidesurface tends to repel the anionic nitrate in the medium [55].

Because the influence of pH on coagulants depends on the reactions that are formed under various circumstances, the rate of hardness removal increases as pH increases.

In neutral conditions:

$3Al_{(s)} + 8H_2O_{(l)} \rightarrow Al(OH)_{2(s)} + 2Al(OH)_3 + 4H_{2(g)}$

In acid conditions

$2Al_{(s)} + 6H_2O_{(l)} \rightarrow O_2\ (g) + 4H_{2(g)} + Al(OH)_{2(s)}$

In alkali conditions

$2Al_{(s)} + 6H_2O \rightarrow 2Al(OH)_{3(s)} + 3H_2O_{(l)}$

In these equations, $AL(OH)_3$ and $AL(OH)_2$ settle while H_2 gas moves upward and causes flotation. As reactions show, in acidity condition $AL(OH)_2$ and in alkali condition $AL(OH)_3$ are produced. Since $AL(OH)_3$ settles more quickly due to its greater density and weight, its efficiency is also higher. As a result, it functions better when embedded in a precipitate [56] [57]. This outcome was consistent with Ghernaout's 2008 study on the electrocoagulation technique for removing Escherichia coli from surface water [57]. Hence, according to the findings of this study and other investigations, the electrocoagulation process can serve as a ph moderator [32]; [35].

The contamination begins to settle at a particular pH. As the medium's pH rises or falls, the effectiveness of pollutant removal reduces. Under some circumstances, the electrochemical AL^{3+} polymerization and hydrolysis reaction may produce complex chemicals and polymers. At pH 4-9, using an Al anode electrode will form $AL(OH)^{2+}$, $AL(OH)_2^{+}$, $AL_2(OH)_2{}^{4+}$, $AL(OH)_3$, and $AL_{13}(OH)_{32}{}^{7+}$. $AL(OH)_4^{-}$ is dominant at a medium of pH higher than 10, then the coagulant production process will regularly reduce [30].

3.5 Electrode distance

The most essential factor in the electrocoagulation process is the effective electrode surface area and the inter-electrode distance [58]. The resistance between the electrodes would rise as their distance grew, necessitating more potential to overcome it. So, the cost of the process will be increased. However, the interaction between the ions and hydroxide polymers should ideally decrease as the distance between the electrodes increases. The voltage drop will rise as the inter-electrode distance rises at constant anode surface area and solution conductivity [59].

It can be seen that decreasing current density occurs when the distance between theelectrodes is increased [29].

The highest pollutant removal effectiveness is attained by maintaining the ideal spacing between the electrodes. The effectiveness of pollutant removal is limited at short distances. This is because the strong electrostatic attraction causes the floc created by the metal hydroxide to deteriorate when it collides with another floc. Due to a reduction in the electrostatic effect, which causes the generated ions to move more slowly as the distance between the electrodes increases, the effectiveness of pollutant removal increases. As a result, the metal hydroxide has more time to produce and agglomerate the floc, increasing pollutant removal effectiveness. Additionally, it should be noted that energy consumption will be affected if the electrode gap widens [30].

khandegar discovered that the ions and species in the solution need more time to move between electrodes at greater electrode distances, which reduces electrostatic attraction and decreases the creation of flocs necessary to coagulate the desired species [60]. According to the equation that describes how electrical resistance varies, it is accurate to say that when electrode distance is increased, ion transport is obstructed, decreasing process efficiency and increasing energy consumption. In electrocoagulation, a thin layer (film) of metal hydroxide forms on the anode surface over time, increasing ohmic loss. As the inter-electrode distance increases, the problem gets worse. The applied potential must rise to maintain a consistent current density; as a result, there may be increased resistance, which would impede anode dissociation. It is undeniably true that lower anode oxidation and cation production result in lower removal efficiency [61]. The electrostatic attraction diminishes, which minimizes the formation of flocs required to coagulate the pollutant [46].

3.6 Sodium Chloride

From different previous researches, It is clear that increasing the chloride concentration increases the removal due to increased mass transport of chloride ions to the anode surface and increased diffusion in the diffusion layer of the anode. As a result, more amount of chlorine/ hypochlorite will be generated. Hence the rate of removal was increased [62] [63].

Another research shows that during the initial periods of electrolysis, the voltage increases sharply until a maximum value. After that, the voltage decreases to reach a pseudo-stationary value. Moreover, the maximum voltage value and the duration time required to achieve the pseudo-stationary plateau are much higher with lower NaCl concentrations. As NaCl dose increases, the cell voltage decreases rapidly.

In one of the studies, one can observe that the amount of aluminum generated increases rapidly as the NaCl dose rises. Subsequently, the quantity of Al^{3+} (coagulant) produced becomes almost constant [64].

It is observed that the amount of aluminum generated increases rapidly as the NaCl dose varies from 0 to 15 ppm. However, the quantity of Al^{+3} (coagulant) produced beyond this concentration becomes almost constant. This indicates that increasing the NaCl concentration up to a certain point enhances the generation of Al^{+3}. In addition, increasing the chloride concentration in the electrocoagulation process positively impacts the removal of pollutants. The higher chloride concentration facilitates the mass transport of chloride ions to the anode surface and increases diffusion in the diffusion layer of the anode. Consequently, more chlorine/ hypochorite will be produced, resulting in accelerated rate removal[64].

3.7 Initial concentration

In an electrocoagulation process, the initial concentration factor refers to the concentration of the target substance or contaminants in the wastewater or solution at the start of the treatment. It plays a significant role in determining the effectiveness and efficiency of the electrocoagulation process in several ways.

It is important to note that the specific relationship between the initial concentration factor and the electrocoagulation process can vary depending on the nature of the contaminants, the electrode material, and the process conditions.

Furthermore, a higher initial concentration of the contaminant leads to an elevation in electrical conductivity resulting in a reduction of metal ion (iron and aluminum) released from the electrode surface. This occurs because it prompts the formation of a passive layer on the electrode surface and increases impedance modulus within the system [65].

When maintaining a constant voltage, a nearly fixed quantity of ions is released by creating metal hydroxide complexes and flocculants as coagulants. Consequently, as the concentration of contaminants rises, the quantity of coagulant rises; this quantity becomes inadequate for effective sedimentation. Additionally, an increase in the initial concentration of contaminants results in highlighted oxidation reactions at the electrode surface, decreasing the anode electrode’s efficacy in releasing metal ions and generating hydroxyl radicals [66][67].

3.8 Operating Temperature

When the temperature is too high, the large pores of the $Al(OH)_3$ gel shrink, resulting in more compact flocs that are more likely to deposit on the surface of the electrode.

Higher temperature gives a higher conductivity hence lower energy consumption[24].

Numerous researchers have investigated the influence of solution temperature on the performance of the electrocoagulation reaction, as the temperature of the solution is a fundamental parameter that affects process efficiency[68].

Previous work findings indicate that the elimination of phosphate ions is enhanced as the solution temperature rises to 60°C. However, byond this temperature, the removal efficiency of phosphate ions decreases.

Raising the solution temperature can improve the transfer of ions from the anode or cathode surface to the solution bulk. This improvement is attributed to reduced solution viscosity and increased ion diffusivity. The reduction in the efficiency of phosphate removal observed at solution temperatures exceeding 60°C can be attributed to the increased passivation of the metal anode and cathode. This passivation occurs due to the formation of protective metal oxide layers, which leads to decreased Mn^{+} ions and ultimately impacts the performance of the electrocoagulation reactor. Furthermore, it has been noted that higher temperatures can cause the contraction of larger pores within the metal hydroxide gel, resulting in the formation of dense flocs that are more prone to depositing on the electrode surface. Additionally, increasing the temperature enhances the solubility of aluminum. However, the effect of temperature on removal efficiency can vary depending on the specific mechanism involved in pollutant removal [69].

According to Vasudevan study, the amount of cadmium removal by the absorption increased with increasing temperature [70].

3.9 Time

The duration of the electrolytic process has an impact on the efficiency of the treatment. The electrode dissolution at the anode during electrolysis results in the generation of coagulating species. In one of the studies, the effectiveness of the dye removal is directly related to the concentration of metal ions produced on the electrodes. As the electrolysis period is extended, the concentration of metal ions and their hydroxide flocs also increases [71].

Another research finding was, during the treatment of leachate using the electrocoagulation (EC) process, it was observed that increasing the electrolysis time improved turbidity removal [72].

Energy and electrode consumption also tend to increase as the reaction time increases in the electrochemical process. This highlights the significance of reaction time as a crucial parameter that impacts the cost-effectiveness of the electrocoagulation process in treating polluted waters[73].

The treatment efficiency of the electrochemical process is also influenced by the reaction time. The duration of electrolysis time (t) plays a crucial role in determining the rate at which Fe^{+2} or Fe^{+3} ions are produced from the iron electrode [74].

There are a lot of studies regarding EC, Table 1 shows some of the latest researchs, in this table different factors were studied. Some of the main factors will be summarized below:

Table 1,
Survey for previous researches

Reference	treated water	removal		electrodes	factors
[75]	village water in serilanka	83% 99%	hardness floride	Al	time current density
[76]	ground water	98.60%	arsenic	Al	the precence of phosphate, silicate, biocarbonate , flouride, boron Time
[77]	wastewater	84% 96% 99% 80.00%	BOD P FC COD	Al	pH time packed density current
[78]	simulated contains calicium , turbidity	36% 93.50%	calicium turbidity	Al	initial calicium conc. initial turbidity time current density
[79]	well in Weld County, and well in Oklahoma	97.30% 34.80% 47.80% 87.80% 37.40% 54%	turbidity COD BOD turbidity COD Doc	Al Fe	electrode material initial pH applied current contact time no. of electrodes
[80]	a secondary treated wastewater from Doha Plant	88.30% 82.40%	total phosphorous COD	Al	symmetric and unsymmetric electrodes AC, DC current time current density
[81]	Chlorella vulgaris suspension	88% (Fe) 73% (Al)	Chlorella vulgaris Chlorella vulgaris	Anode: Fe/Al Cathode: stainless steel	

[63]	simulated wastewater	98% 90%	dye COD	Al	pH initial concentration NaCL concentration voltage EC versus CC current density
[82]	ground water / vienna, untreated water from lake in Ohio	100% 100%	Perfluorooctanoic acid microcystins	Al	reversed polarity voltage pH
[83]	by product produced by oil gas industry	99%	TSS	Al	current density
		100%	oil&grease		
		89.7% removal of TSS with steel slag containing system compared with conventional system without steel slag 55.7%removal			residance time steel slag concentration
[84]	municipal wastewater	100% 80% >90% >90%	TP(total phosphorus) TN (total nitrogen) TOC Turbidity	Graphite/cathode, Al,Fe/anode	bipolar electrode on EC bipolar electrode on pollutant removal
[85]	Pb-Zn flotation wastewater	37.70%	COD/Al mixedwater	Al/Fe	different wastewater types
	Pyrite concentrate wastewater	62.70%	COD/Fe mixed water		current density
	Pyrite tailing wastewater	25.70%	COD/GAC mixed water		delectrode type
	Mixed wastewater	77.62%	COD/EC mixed water		pH
		>80%	COD/(EC,GAC) mixed water		time
		80.24%	EC/Pb-Zn flotation		addition of Na2SO4
		79.33%	EC/Pyrite concentrate		comparing EC with GAC
		85.05%	EC/Pyrite tailing		Pb/Zn grade recovery
		82.84%	EC/mixed		
[86]	oily saline wastewater from drilling oil sites	17.50% 83.22% 60.38% 22% 25%	TDS TSS HCO3 CL Ca	Al	current density time
[87]	texile wastewater	96 76	DFZ436 COD	Fe	initial pH Current density time
		90 68	DFZ437 COD	AL	
		93% 99% 97% 91%	COD Conductivity Chloride TDS	NF270 membrane	
[29]	river water, iron water, hard water	> 99% 90% 80.72%	Fe Turbidity KMnO4	Al	current time distance between electrodes

[88]	Al-Kut textile wastewater	96.40%	Turbidity	Al/ EC	pH turbidity
		75.40%	Turbidity	Chemical coagulation	conductivity TDS
[51]	synthetic blowdown water of cooling tower	60%	Calicium	Al	current density
		97%	Magnesium		initial pH
		98%	Silica		time 15-60 min.
[89]	model and actual surface waters		TTHM NOM DOC	IronEC/CC	formation percentage during the EC and CC
[90]	raw water(with high turbidity)	84% 86.44%	Color Turbidity	Al	
[91]	groundwater taken Jaffna	85%	Hardness	iron	MP,BP compared voltage surface area to volume ratio initial ph time
[59]	Sawa Lake, Al-Muthanna, Iraq	91%	TDS	Al	current density temperature
		93%	Cl		time 15-60 min.
		92%	Br		pH inter electrode distance
		90%	SO4		stirring speed
[92]	Bore Well Water	89.45%	Hardness	Al	pH
		83.43%	Alkalinity		Current density
		74.07%	TDS		time voltage

4. Conclusion

Use of electrocoagulation for water treatment has been studied for treating drinking water and waste water rectifying. Regarding the efficiency of the process the most important factors that affecting the electrocoagulation process (EC) are electrode configuration, current density, process time, initial pollutant concentration, the pH and the presence of competing ions.

Many studies show that a lot of particles and ions were removed successfully by electrocoagulation such as iron, boron, sulfate, nitrate, hardness, turbidity, silica, viruses, bacteria. It has been noticed that different removal efficiency of different species was varied according to factors mentioned in this article. i.e for the same water sample used the efficiency of removal varied depending on the electrode material type, conductivity of solution, pH of sample, current /voltage applied, distance between electrodes and electrode configuration.

Abbreviation

BOD	biochemical oxygen demand
COD	chemical oxygen demand
P	phosphorous
FC	fecal coliforms
TOC	total organic carbon
GAC	granular activated carbon
TDS	total dissolved solid
TSS	total suspend solid
DFZ436	color value (durchsichts =indexes of transparency)

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العوامل المؤثرة على عملية التخثر الكهربائي لانواع المياه المختلفة: مراجعة

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الخلاصة

من اجل استعمال المياه الخام كمصدر للشرب يجب ان تحتوي على متطلبات فيزيائية وكيميائية وبيولوجية معينة. هناك العديد من الطرق والتقنيات المتوفرة لمعالجة المياه، بالاضافة للطرق التي تستخدم المواد الكيمياوية، طريقة التخثر الكهربائي. وانها طريقة فعالة ومتطورة لمعالجة العديد من الملوثات، بما في ذلك البكتريا والفيروسات والحديد والفلوايد والكبريتات والبورون، بالاضافة للعسرة والعكارة والمواد الصلبة العالقة والمواد العضوية وغير العضوية و COD، و BOD، واللون. يتم استخدام التخثر الكهربائي بشكل متكرر في معالجة العديد من أنواع المياه ومياه الصرف الصحي. تركز هذه المقالة على التطورات الحالية في التخثير الكهربي لمعالجة المياه وتاثيرات ظروف التشغيل المختلفة. نظرًا لفعاليتها غير العادية في إزالة مجموعة متنوعة من الملوثات. فقد اجتذبت الكثير من الاهتمام مؤخرًا وذلك لقابليتها الاستثنائية في معالجة العديد من الملوثات. تقدم هذه المقالة تحليلاً شاملاً للأدبيات المعاصرة التي تلتزم باستخدام التخثير الكهربي في مجموعة متنوعة من طرق معالجة المياه، مع التركيز على المتغيرات المختلفة التي تؤثر على أداء العملية. المتغيرات الأساسية للمقالة هي التيار الكهربائي، مادة المستخدمة القطب، وطريقة ربط الاقطاب، ودرجة الحموضة ،المسافة بين الأقطاب، تركيز كلوريد الصوديوم، التركيز الاولي للملوثات او الايونات، درجة الحرارة والزمن.
