Treatment of Industrial Wastewater through the Process of Electrocoagulation: A Review

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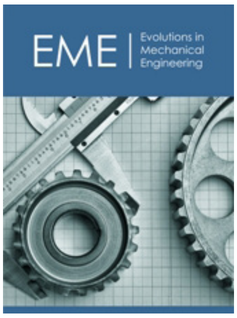
ISSN: 2640-9690



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Submission: October 25, 2023
Published: November 28, 2023

Volume 5 - Issue 1

How to cite this article: Aoha Roohi Amin*, Mahnoor, Muhammad Zeeshan and Tuba Safdar. Treatment of Industrial Wastewater through the Process of Electrocoagulation: A Review. Evolutions Mech Eng. 5(1). EME.000603. 2023.
DOI: 10.31031/EME.2023.05.000603

Abstract

Several different approaches are employed for wastewater treatment to reduce the quantity of harmful substances that are let out into the surroundings each year from a variety of industries. By electrochemically dissolving sacrificial anodes, often formed of iron or aluminum, the Electrocoagulation (EC) technique destabilizes contaminants that are dissolved, suspended, or emulsified. It has the capacity to eliminate a range of pollutants from various types of wastewaters, including organic and inorganic contaminants. The pH, electrode, operating period and current density are only a few of the variables that affect how well the EC process works. Reviewing the most pertinent newly published material is the aim of this study. The electrode passivation and energy use issues with the EC technique are the key difficulties. EC has benefits over other conventional technologies, including lower operational expenses and lower energy use. A survey of the literature covering electrocoagulation electrochemical treatment of wastewater published during the previous 32 years was given. The review discusses issues about electrocoagulation, the background electrocoagulation hybrid process for industrial and leachate wastewater treatment and its cost effectiveness.

Keywords: Electrocoagulation; Electrodes; Wastewater treatment

Introduction

Today, the detrimental effects of contaminated water and wastewater, as well as the depletion of water resources, are undeniable global problems. The most significant environmental issues of the twenty-first century are pollution and water recycling. Industrial wastewater is defined in a very broad sense and differently from home wastewater. The effluent's composition and characterization are entirely varied and extremely complex because of the numerous types of industries and application processes [1]. Industrial effluent can be classified into different categories depending on the harm it causes to the environment [2]. Electrocoagulation (EC) has been used effectively as a first treatment in the elimination and modification of polycyclic aromatic hydrocarbons from industrial effluents [3,4]. The Fe or Al anode is oxidized during wastewater treatment electrolysis, yielding corresponding metal ions that instantly hydrolyze to polymeric iron or aluminium hydroxide. These polymeric hydroxides are good coagulants, and the tiny oxygen and hydrogen bubbles created by the anode and cathode may help in particle flocculation in the wastewater [1]. It should be noted that water treatment methods seem to be the most effective way to lessen the impact of pollution on aquatic and aqueous systems. Every wastewater treatment facility tries to address the previously mentioned environmental issues. Physical-chemical treatments are the most common type of treatment.

Since they have been used for producing drinkable water for people for ages [5]. The harmful substances found in wastewater are now entirely distinct and complex because of industrial operations and technological advancement. As a result, research into water treatment techniques has been crucial to treating the growing pollution. Table 1 shows the breakdown of dangerous compounds found in industrial effluent and their likely sources.

[6,7]. Many traditional methods/units are used to treat industrial water, coagulation has fewer advantages and disadvantages, so scientists introduce the hybrid method called electrocoagulation, which is more effective and reasonable than coagulation [6]. Electrocoagulation (EC) has been used effectively as a first treatment in removing and transforming polycyclic aromatic hydrocarbons from industrial effluents. EC is a chemical and physical technique that injects ions into wastewater using consumable electrodes such as Fe or Al [8]. The Fe or Al anode is oxidized wastewater treatment electrolysis, yielding corresponding metal ions that instantly hydrolyze to polymeric iron or aluminium hydroxide. These polymeric hydroxides are good coagulants, and the tiny oxygen and hydrogen bubbles created by the anode and cathode may help in particle flocculation in the water [9] (Table 2).

Table 1: Contaminants in wastewater and their potential sources.

Contaminant	Potential Sources
Heavy metals	Mining operations, metal processing, electroplating
Organic compounds	Chemical manufacturing, petroleum refining
Suspended solids	Construction sites, mining operations
pH imbalance	Chemical manufacturing, metal processing
Oil and grease	Automotive maintenance facilities, oil refineries
Nutrients (e.g., N, P)	Agricultural runoff, food processing
Toxic chemicals	Pharmaceuticals, pesticide manufacturing
Chlorinated	Chlorine-based disinfection, chemical
compounds	manufacturing
Bacteria and viruses	Food processing, wastewater treatment plants
Radioactive elements	Nuclear power plants, radiological laboratories

Table 2: Conventional operational units and their description (Yusmartini et al. [19]).

Operational Unit	Description
Screening	Removal of large solids, such as debris and trash
Grit Removal	Removal of heavy inorganic solids, such as sand and gravel
Primary Sedimentation	Settling of suspended solids and heavy organic matter
Equalization Tank	Mixing and storage of wastewater to balance flow and composition
Aeration Tank	Introduction of air or oxygen to promote biological treatment
Secondary Sedimentation	Separation of biological sludge and treated wastewater
Filtration	Removal of remaining suspended solids through media filtration
Disinfection	Elimination of pathogens and harmful microorganisms
Sludge Treatment	Processing of separated sludge for further treatment or disposal

This review article aims to focus on the EC affecting factors in the cripples & fundamentals of the EC process, theory related to its mechanism and potential applications in different areas. $Al_{3}^{+}{}_{(aq)}$ and $OH^{-}{}_{(aq)}$ ions produced by reactions at electrodes and form numerous monomeric species, which changes finally into $Al(OH)_3$ by complex precipitation kinetics [10]. The electrostatic antiparticle repulsion is reduced to the point that van der Waals attraction takes hold, resulting in coagulation. There is no net fee because of the procedure. (C) Flocs formation: Colloidal particles that remain in the aqueous medium are trapped and bridged by the sludge blanket created by merged flocs. In a parallel process, water is electrolyzed to produce small bubbles of hydrogen at the cathode and oxygen at the anode. [11]. By drawing flocculated particles to them, these bubbles cause the pollutants to rise to the surface due to their inherent buoyancy. More effective coagulants than those used in chemical dosing are hydroxides, ox hydroxides, and polymeric hydroxides. They can precipitate or adsorb dissolved contaminating species, destabilize colloidal suspensions and emulsions, and create flocs that may be removed by flotation or settling/filtration [12] (Figure 1).

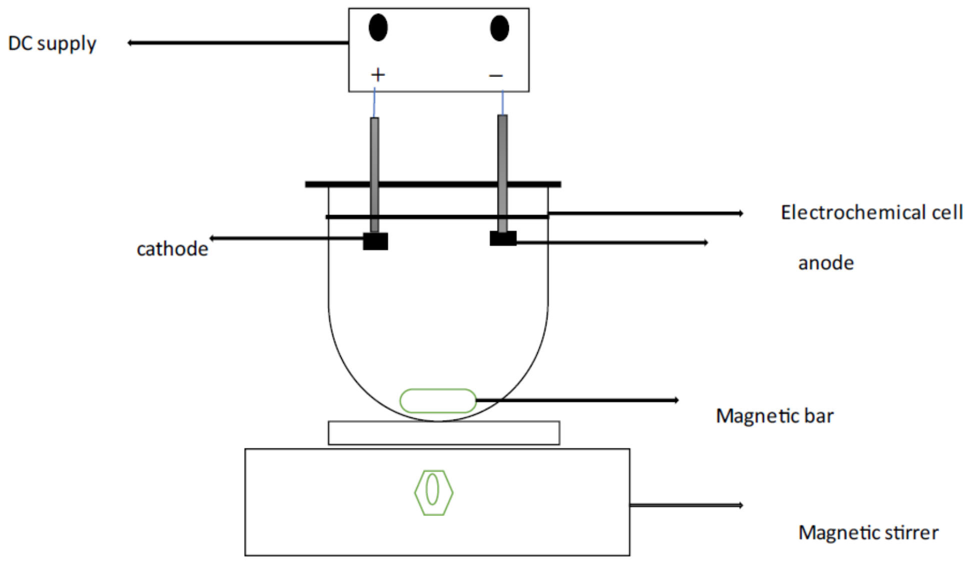

Figure 1: Experimental Setup of Electrocoagulation process.

Principles of electrocoagulation

An electrochemical cell is used in the EC procedure to treat the water. An electrochemical cell's main components are the anode and the cathode, which are dissolved in an electrolyte or conducting solution and connected by an electrical circuit to provide a current source and a control device [5]. The anode's metallic cations hydrolyze to generate hydroxides, poly hydroxides and poly hydroxyl metallic compounds with a strong attraction for scattered particles and counter ions, causing coagulation. By decreasing the repulsive potential of the electrical double layer, they may decrease the net surface charge of colloidal particles in suspension [13]. Therefore, the repulsive interactions between colloidal particles weaken, bringing the particles together to the point where van der Waals forces prevails and particle agglomeration occurs. It should be noted that, unlike chemical coagulation, the processes of flocculation and coagulation in EC happen simultaneously and cannot be differentiated from one another. The two processes, flocculation and coagulation, are physically separated or differentiated when metal salts are used in water treatment facilities based on the amount of time required for each ("An Overview of the EC Process for the Treatment of Wastewater," 2018) [14] (Figure 2).

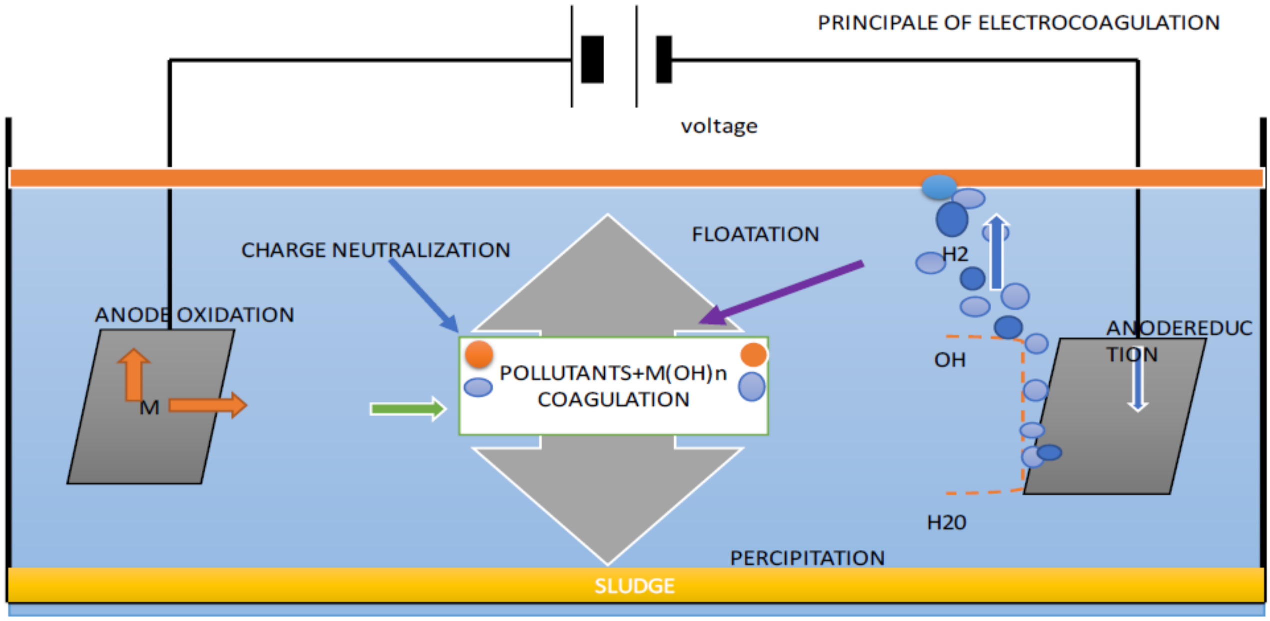

Figure 2: Main principle of EC Procedure.

Fundamentals of electrocoagulation and oxidation (Electrocoagulation Oxidation (ECO))

A comprehensive understanding of the fundamentals is crucial to comprehend the underlying mechanisms of ECO. Electrocoagulation (EC) involves destabilizing and coagulating pollutants present in wastewater by applying an electric current [15]. The process typically takes place in an electrolytic cell, where the wastewater acts as the electrolyte. When a direct current is applied, metal species (such as aluminium or iron) are released from the electrodes, generating metal hydroxide species. These species act as coagulants and aid in removing pollutants through coagulation, flocculation, and sedimentation processes [16]. Several important variables, such as the electrode material, current density, pH, and treatment duration, affect how successful EC is. The kind and concentration of metal ions emitted during electrocoagulation are determined by the electrode material chosen, therefore choosing wisely is essential [17]. Iron and aluminum are frequently utilized as electrode materials due to their affordability, availability, and effectiveness in generating coagulants. However, other materials such as titanium, stainless steel, and graphite have also been investigated for their suitability in specific applications [18].

In addition to electrocoagulation, integrating oxidation processes with EC has attracted a lot of attention lately, leading to the development of Electrocoagulation Oxidation (EC0) as an advanced treatment approach. Incorporating oxidation techniques aims to increase the degradation and mineralization of recalcitrant pollutants that are not effectively removed through traditional electrocoagulation alone [19]. Electrochemical oxidation is a widely explored technique that utilizes the electrochemical generation of most reactive species to degrade organic compounds in wastewater. Commonly employed anodes for electrochemical oxidation include Boron-Doped Diamond (BDD), Mixed Metal Oxide (MMO), and Platinum Group Metal (PGM) electrodes [20]. These anodes facilitate the amount of Reactive Oxygen Species (ROS), potent oxidants capable of breaking down complex organic molecules into more direct, less harmful by-products. Several studies have demonstrated electrochemical oxidation's effectiveness in degrading organic dyes, pharmaceuticals, and other persistent pollutants [21].

Another promising oxidation technique combined with electrocoagulation is photo electrochemical oxidation. This approach utilizes the synergistic effects of light and electrochemical processes to enhance the degradation of pollutants. Typically, a photoactive semiconductor material, such as titanium dioxide (TiO_2), is incorporated into the EC system [22]. When illuminated with UV or visible light, the photo excited electrons and holes generated on the surface of the semiconductor promote redox reactions, facilitating the degradation of organic pollutants. Photo electrochemical oxidation has shown promising results in treating various organic contaminants, including pesticides and emerging micro pollutants [21]. Sono-electrocoagulation is another innovative approach that combines the application of ultrasound with electrocoagulation. Ultrasound waves generate cavitation, leading to micro bubbles forming and collapsing in the wastewater [23]. The collapse of these micro bubbles produces shockwaves and localized high temperatures and pressures, creating an environment conducive to oxidation and enhancing pollutant degradation [24].

Numerous investigators have made noteworthy contributions to the comprehension and progression of EC0 technology. To achieve high removal efficiency, for example, a thorough analysis was carried out on the use of EC0 to treat pharmaceutical effluent. Their research emphasized the role that optimization factors have on EC0 system performance [20]. Furthermore Sari et al. [25] centered on treating wastewater containing dyes by combining photo electrochemical oxidation and electrocoagulation. Their study showed how the integration of light- responsive semiconductor materials might facilitate effective electron-hole separation and subsequent pollutant oxidation, hence optimizing the degradation of dyes by photo electrochemical oxidation. Additionally, Chakchouk et al. [22] examined how well sono-electrocoagulation worked to remove organic pollutants from wastewater. Comparing their study to traditional electrocoagulation, they found that the combined effects of ultrasound and electrocoagulation led to higher rates of pollutant breakdown. The researchers emphasized the importance of optimizing process parameters, such as applied current, pH, and ultrasonic frequency, to maximize the sono-electrocoagulation efficiency (Figure 3).

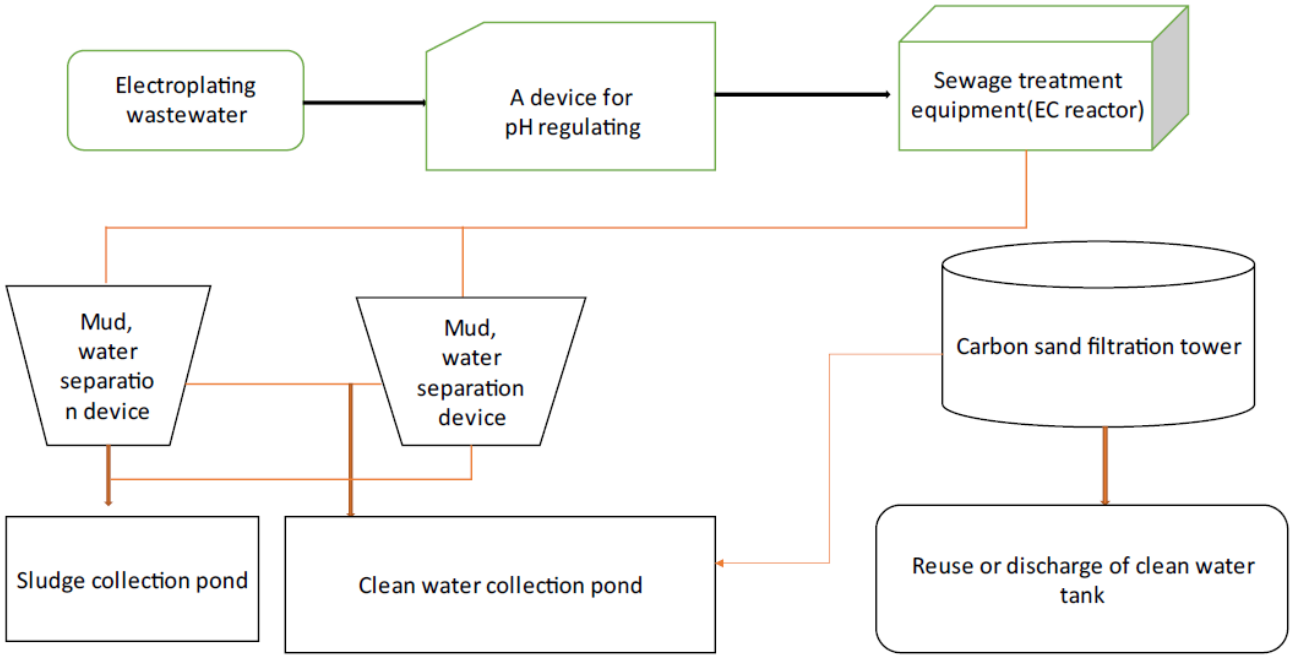

Figure 3: Flowchart Showing Electrocoagulation treatment.

Applications of Electrocoagulation

Wastewater treatment

Wastewater treatment is a critical area where Electrocoagulation (EC) has gained significant attention due to its effective removal of contaminants. This section reviews the work conducted by different researchers in exploring the potential applications of electrocoagulation. These researchers use different electrodes to examine which electrode has more removal efficiency and are costlier. Some researchers, like El-Ashtoukhy et al. [26], examined the use of EC to remove heavy metals from industrial wastewater and emphasized the significance of optimization factors like pH and current density Ravadelli et al. [27] explored the application of EC for dye-containing wastewater treatment, focusing on the influence of electrode material, current density, and initial dye concentration An et al. [28] studied the treatment of oil-water emulsions using EC and investigated vital factors Zodi et al. [6] conducted a comprehensive review of EC for industrial wastewater treatment, covering mechanisms, electrode materials, optimization parameters and performance evaluation Gil Pavas et al. [29] examined the removal of organic pollutants from wastewater using a combination of EC and activated carbon adsorption, highlighting the synergistic effects of the two processes Zaied et al. [12] investigated the removal of pharmaceutical compounds from wastewater using EC and discussed the factors affecting their removal efficiency. Ammar et al. [30] explored the application of EC for treating petroleum refinery wastewater, focusing on removing oil, suspended solids, and heavy metals Huda et al. [31] studied landfill leachate treatment using EC and evaluated the influence of electrode materials, current density, and initial leachate characteristics on the process efficiency Parga et al. [32] investigated the removal of arsenic from groundwater using EC and discussed the impact of operational parameters on arsenic removal efficiency. Moussa et al. [33] examined turbidity removal from water using EC and analyzed the effects of various factors, including current density, electrode spacing, and water pH Bilińska et al. [34] focused on treating textile wastewater using EC and evaluated the influence of electrode material, current density, and initial pollutant concentration on the removal efficiency. Alaton et al. [35] studied the removal of organic dyes from wastewater using EC and discussed the effects of process parameters on decolorization efficiency.

Galvão et al. [36] explored the application of EC for treating landfill leachate and discussed the removal efficiency of pollutants such as COD, ammonia and heavy metals. Phalakornkule et al. [37] investigated the removal of Total Organic Carbon (TOC) from industrial wastewater using EC. They discussed the effects of electrode material and current density on TOC removal efficiency. Zheng [9], Ammar et al. [38] explored the application of EC to treat oilfield-produced water and discussed the removal efficiency of oil, suspended solids and heavy metals. Song et al. [39] investigated the removal of arsenic from groundwater using EC and discussed the influence of operational parameters on nitrate removal efficiency. Thakur et al. [7] studied dye wastewater treatment using EC and evaluated the effects of electrode material, current density, and electrolyte concentration on decolorization efficiency. In addition to the studies mentioned above, numerous other research papers have contributed to the understanding and advancement of electrocoagulation for wastewater treatment. These studies have explored various aspects, such as pollutant removal mechanisms, optimization parameters, electrode materials, and treating specific wastewater types. Collectively, these works provide valuable insights into the applications and potential of electrocoagulation as an efficient and sustainable wastewater treatment technology. The Table 3 given below highlights the key points of other researchers.

Table 3: Application and effectiveness of electrocoagulation process for different industrial wastewater.

Sample	PH	Current Density mA/cm²	Operation Time (min)		Dense Coagulant (mg/l)	Electrode/ Chemical Coagulant	Percentage Removal (%)		Author
Synthetic	4	40	15		NA	Aluminum electrodes	99(a)	83(cr)	[2]
Potato Chips	5	20	30		NA	Aluminum electrodes	60(COD)	98(ss)	[2]
		20	30		NA	Iron electrodes	50(COD)	80(ss)	[45]
Textile Water	EC PH 6.9 CC PH 5.5	10	20		NA	Aluminum electrodes	63(c0d)	NA	[46]
		10	10		0.8 kg/m³	Aluminum electrodes + Poly aluminium chloride	80(c0d)	NA	[46]
		10	10		0.8	Aluminum electrodes + alum	65(c0d)	NA	[46]
		NA	NA		0.32	Poly aluminium chloride	78(c0d)	NA	[24]
		NA	NA		0.32	alum	72(c0d)	50	[47]
Slaughterhouse	7.31	40v	60	25		Aluminum electrode + Propyl ammonium chloride	37(c0d)	47 (SS)	[48]
		NA	NA	25		Poly aluminium chloride	37(c0d)		[49]
Distribution Network	10	24	60	NA		Iron electrodes	98(c0d)	97(TOTAL HARDNESS)	[48]
Restaurant	10-Jun	30-80	NA	NA		Aluminum electrodes	90(c0d)	94(OIL AND GREASE)	[50]
Industrial Wastewater (San Rafael-Mins ur S.A Mine)	6.6-8	22.35	45	NA		Iron electrode	99.17(Fe) 99.97(Mn) 99.35(TS S)	90(cu, Zn, Cd)	[51]
Oil Refinery (Conchan)	8-9	50	30	NA		AL Anode	98(NTU) 60(oil and fats)	32.27 (phenol)	[52]
Waste Disposal Plant (Be fesa-Peru)	8-8.3	110	30	NA		Iron anode	95.6(NT U)	45.14(COD)	[53]
Industrial Wastewater (Billet Industry)	5	98	30	NA		AL anode	99(PB) 99(Cr)	99(zn)	[54]

Wastewater	7	20-25	45			Al anode + cl	99(Cr)		[55]
Sewage Water	7-9	1816	30	NA		Iron electrode	96.14(C0 D) 96.14(COD)	92(SS)	[56]
Sewage Water	7-9	1816	30	NA		Al electrode	97.64(CO D) 96.17(B0 D)	94.9(SS)	[23]
Wastewater	7	44	30	NA		Al + stainless steel	99(Cu,Ni, Cr)		[48]
Sewage Water	7-9	1816	30	NA		Stainless steel	98.07(CO D) 98.07(BOD)	95.69(SS)	[57]

Leachate treatment

Landfilling is the most prevalent and convenient method of disposing of solid waste. The dump often receives garbage from municipalities close to the site. If the site of trash generation is distant from the transfer station, there is a method to cut garbage transportation costs. In most cases, waste items from residential, business, and institutional areas were mixed. Landfills produce three types of outputs: gas, liquid (leachate), and inert solids [40]. Leachate is difficult to treat due to its complicated structure and high pollutant load. They become the primary pollutant of wastewater because it is the most difficult to treat due to the complex and wildly varied content created inside landfills [41]. Many different sorts of contaminants may be found in leachate wastewater. Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (C0D), ammonia and high concentrations of several metals are indicators of complex pollution. The presence of these contaminants in high concentrations harms the ecosystem. As a result, many therapies and pre-treatments work together to prove that they treat Leachate [42]. Membrane processes, sophisticated oxidation techniques, coagulation- flocculation procedures, and lagoon and wetland applications are some well-known technologies used for leachate treatment. However, they are costly and difficult procedures, and a developing no tendered simple ones. Electrocoagulation is a simple technique for successfully treating wastewater [14].

Because of its great efficiency and cheap maintenance, this electrochemical therapy seems to be a potential therapeutic choice. Less effort is needed and results are obtained quickly (Table 4 & 5). For a particular pollutant, electrocoagulation may supply a choice for employee other chemical coagulation like astral salts or polymers. The electrode may produce coagulated species and metal hydroxide, which help to stabilize and agglomerate suspended particles [43]. The hydrogen gas emitted by the cathode, which aids in the flocculation of particles in water. The electrocoagulation technique is dependable and cost-effective, producing little sludge and showing no sensitivity to hazardous metals. A coagulant is produced by the electrolytic oxidation sacrificial cathode by using a direct current [44] (Figure 4).

Table 4: Leachate properties at different pH.

Sample	Current Density	Operation Time(min)	Dose Coagulant(mg/l)	Electrodes/Chemical Coagulant	Percentage % Removal		Author
Leachate (PH4)	10V	100	NA	Aluminum electrode	74 (C0D)	NA	[58]
Leachate (PH5)	75mA/cm^2	NA	NA	Aluminum electrode	48(C0D)	NA	[19]
Leachate (PH5.8)	9V	35	NA	Aluminum electrode	96(C0D)	97 (turbidity)	[59]
Leachate (PH6)	60mA/cm^2	30	NA	Iron electrode	81(C0D)	72 (colors)	[18]
Leachate (PH6.5)	2.98mA/cm^2	30	NA	Iron electrode	33(C0D)	25 (ammonia)	[60]
	2.98mA/cm^2	30	NA	Aluminum electrode	21(C0D)	20 (ammonia)	
	4.96mA/cm^2	90	2319	Iron electrode +sodium chloride	93(C0D)	39 (ammonia)	
Leachate (PH8.65)	10V	120	1.5% (w/v)	Charcoal Composite Electrodes (C70-PVC30) + sodium chloride	82(C0D)	69 (ammonia)	[61]
Leachate (PH8.2)	34.8ma/cm^2	30	NA	Aluminum electrode	59(C0D)	NA	[62]
				Iron electrode	33(C0D)	NA	
	NA	NA	1500	Alum	31(C0D)	NA	

Table 5: Types of pollutant removal.

Types of Wastewaters	Removal Parameter	Anode-Cathode	Current Density(A/m^2) Current or Voltage	Time in Minutes	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 62.5	[63]

Oil-water	Palm oil cod, ss, tds	Al-al	20-60	5-15	5	72 64 53 43	[53]
Nitrate water	Cr 5	Fe, al-al	10-20v	12-60	7	89.5	[64,65]
Domestic wastewater	Cod turbidity phosphorus	Fe-fe, al-al	10-150	5-40	7.8	72 98 98	[66]
Textile wastewater	Cod dyestuff	Fe hexagonal wire	200	90	7	93 93	[36]
Textile wastewater	4 synthetic dyes	Al-al	251.6	60	6.5-9.7	87-97	[67]
Textile wastewater	Orange II dye	Fe-fe	30v	30	7.5-10	60-92	[68]
Domestic wastewater	Cod, TDS	Fe-fe	0.12-0.36A	5-20	6.7	90 90	[69]
Synthetic wastewater	polyphosphate	Steel	11.5	60	7.2	99.85	[70]
Synthetic wastewater	Amp shmp	Steel	10-60V 0-5A	60	7-7.5	98.84 97.95 97.75	[71]
Dairy Wastewater	Cod Bod TSS	Al-al	80	15-60	7.2	80	[72]
Textile wastewater	Mb dye	Fe-fe	10-40V	10-20	12	80	[73]
Textile WW	Azo dye (ry 14)	Fe-fe	100-300	10-25	2	99	[74]
Textile WW	Rs dye	Fe-fe	50-125	0-90	7.1	96.56	[75]
Textile WW	Cod turbidity	Fe-fe	10-30V	0-60	5-7	79 96	[56]
Hospital WW	Cod	Fe-fe, al-al	10-60V 0-5A	30-60	3-11	87	[76]
Textile WW	Br 18 dye	Al-al	2-5V	10-60	3-11	97	[77]
Dying WW	Rr 195 dye	Fe-fe	140-170	0-30	3-12	99	[78]
textile WW	Br dye 5001 b cod	Fe-fe	10-50	0-60	9	76 95	[54]
textile WW	Rg 19 dye	Al-al	0.3-24V	10-60	3-11	99	[79]
synthetic WW	Polyphosphate	Steel	150-250	0-60	7.2	85-99	[44]
textile WW	Mb dye	Fe-fe, al-al	50-650	2-24	3-9	100 95	[80,81]
dying WW	Azo 2 naphthol dye	Al-al	4.5-10.5V	0-120	7	90	[82,83]
Dying WW	Crystal violet dye organic dye	Al-ss	50-300	10-60	3.5-5.5	99 98	[33]
Sewage WW	TSS, TDS, cod	Fe-fe	60-140	3-30	5-12	85-99	[2]
Oily WW	Cod diesel	Fe-fe, al-al	0-100	10-90	3-11	--------	[3]
Synthetic WW	Rr 141 dye	Fe-fe	15V	0-55	7.2	99	[4]
Synthetic WW	Nitrate	Al-al	50-200	10-30	3-9	98.8	[5]
Textile WW	Color turbidity	Fe-fe Al-al	100-250	5-35	7	99.88	[13]

Textile WW	Malachite green dye cod	ss-ss	13.9-138.9	0-15	3.5-5.5	91	[44]
Textile WW	Reactive red 24 dye cod	Fe-fe, al-al	50-200	0-30	5-12	90 97	[84]
Textile ww	Reactive violet 5 dye	Al-ss Fe-ss ss-ss	100-250	0-60	3-11	99 85	[56,85]
Aqueous solution	Brilliant green dye	Fe-fe	13.9-138.9	15-75	4-12	99.6 91	[83]
Textile WW	Azo RR 29 dyes Azo DB 79 dyes	ss-ss	15.7-35 15.7-40	0-60	7-11	22 91.5	[86]
Dairy WW	Conductivity turbidity	Al-al	5-24V	15-75	2.3-8.8	99	[87]
Contaminated WW	Malachite green dye	Al-al Fe-fe	20-120	0-30	4-10	98	[88]
Textile ww	Acid black 194 dye	Fe-fe	5-100	0-60	1.8-10	93 94	[89]
Paint industry ww	Cod	Al-al	0-20	10-40	5.8	99	[19]
Oily WW	Oil and grease suspended solids SS	Fe-fe Al-al	20-200	10-70	1.5-10	Over 75	[90]

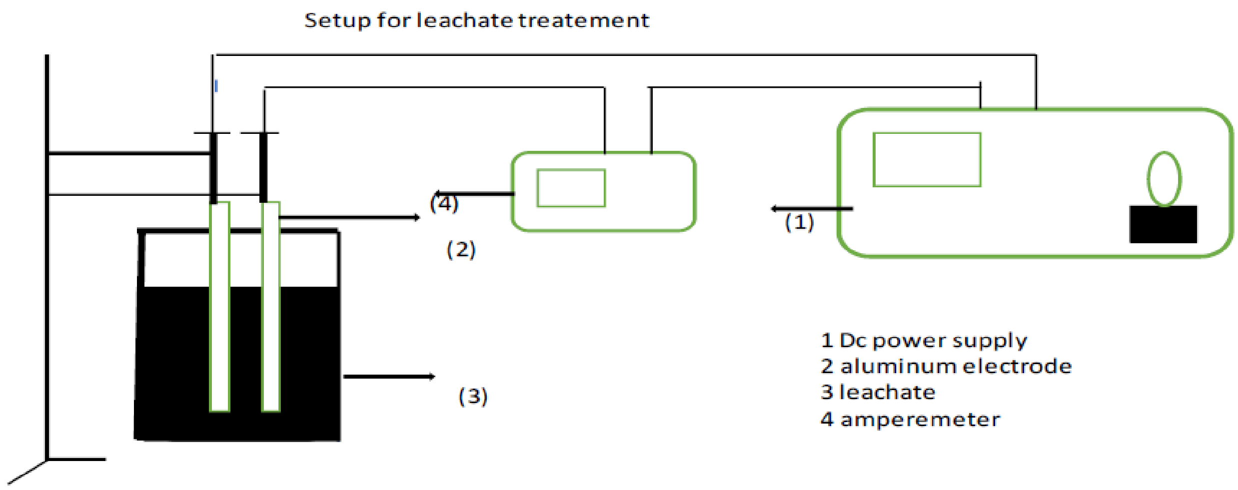

Figure 4: Setup for Leachate treatment.

Factors affecting electro-coagulation

Several variables can alter how effective an EC is at removing impurities from wastewater [45-57]. These variables include the kind of power source, the spacing between the electrodes, the shaking speed, the length of the treatment, the density of the current given, the layout of the electrodes, and the material of the electrode selected [58-62].

Influnce of current density

The electrode material is selected considering factors like the type of contaminant, expected results and chemical orientation of the contaminant present [63-75]. The electrode material not only affects the efficiency of the process but also affects the cost of the system[76-90]. Iron and Aluminum electrodes are extensively used for EC while they deionize into respective ions (Fe_2^+, Fe_3^+, Al_3^+). Several studies have been carried out to compare the Al and Fe electrodes [12,91]. Shen and co-workers while working on micro plastic removal reported a high removal efficiency of (>98.6%) for four different types of micro plastic including (polyethylene, polymethylmethacrylate, cellulose acetate [92]. As the electrocoagulation works on the Coulomb's law of electrostatics, the distance between plates affects the electrostatic field and in turn the removal efficiency [68,93]. Proposed that an increase in the distance between the plates results in a greater removal of pollutants because the MOH ions collisions are hindered due to a little space between electrodes. While a greater agglomeration is possible when ions movement is slow and the possibility of flocs increases gradually (Figure 5). Applied current density is related to the generation of MOH ions and power consumption of the unit. An optimized current density investigation is thus required to operate the system. Galvão et al. [36]; Espinoza- Quinones et al. [67] observed a linear increase in the removal efficiency with increase in applied current density keeping all other parameters same [66] (Figure 6). The coagulant dose and bubble formation rate, the size and growth rate of the flocs, the bubble size, the reaction kinetics, and the energy consumption of the EC are all influenced by the applied current density [26,94]. There is a relationship between the voltage and the applied current density. In an electrochemical cell, higher voltages cause currents to rise and vice versa; but, in certain circumstances, such as when the electrodes are passivized, high over potentials cause currents to fall [70,95].

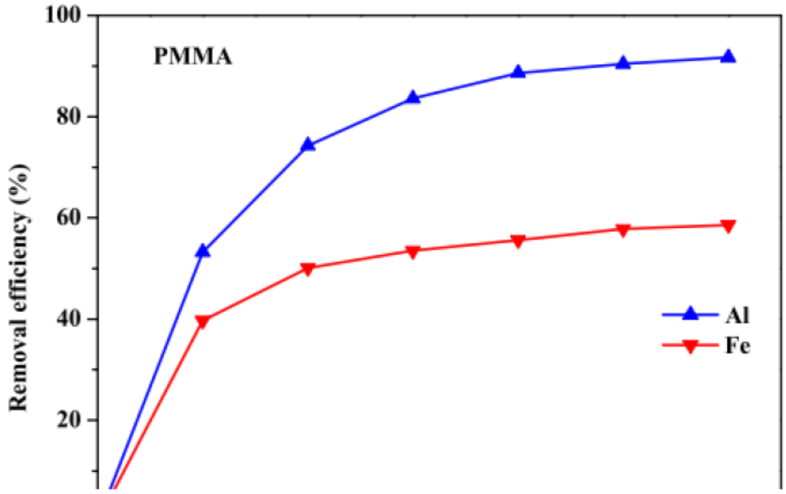

Figure 5: Effect of Al and Fe electrode on removal of micro plastics during electrocoagulation.

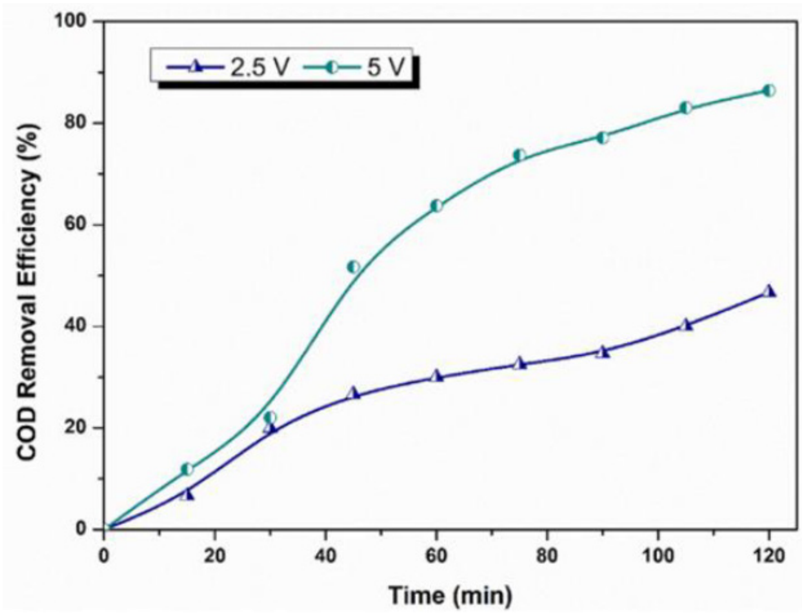

Figure 6

Cost Analysis

With so many wastewater treatment alternatives, cost-effective electrocoagulation is required [96-106]. Kobya et al. discovered that 99.4% cadmium removal, 99.1% nickel removal, and 99.7% cyanide removal could be obtained from electroplating rinse water. The treatment cost $1.05/m^3 for cadmium and $2.45/m^3 for nickel and cyanide if the conditions were best. Remazol Red 3B decolorization using iron electrodes and discovered that under ideal conditions, 99% decolorization was possible. The authors discovered that 3.3 kWh/kg dye could be obtained for 0.6euro/m^3 of energy consumption Chen X et al. [106] decided that fluorescent penetrant liquid may be treated with aluminum electrodes for non-destructive testing in the aviation sector. Using electrocoagulation, the current treatment achieved 95% (COD), 99% colour, and 99% turbidity. This more intensive course of treatment allowed for a 17-week payback period. (Sallam Mohammed et al. n.d.) conducted laboratory experiments and analyses on Oil Bilge Wastewater [OBW] using iron and aluminum electrodes in Bipolar (BP) and Monopolar (MP) configurations. Using best circumstances, electrocoagulation treatment of oil bilge effluent 93% biochemical oxygen demand, 95.6% oil and grease, 99.8% total suspended particles and 98.4% turbidity [107]. According to this analysis, the costs of oil bilge treatment were $0.46/m^3 for energy and electrode consumption, chemicals, and sludge disposal.

Amorphous aluminum hydroxides, current densities, and electrode density were all considered in the electrochemical removal of iron [Fe(II)] from tap water using aluminum electrodes The authors discovered that treating a concentration of 15mg/L Fe(II) concentration would cost USD 6.05/m^3 of tap water. Electrocoagulation with mild steel electrodes was used to treat agro-industry effluent (meat processing, cereal, and food drinks) [21]. In terms of Chemical Oxygen Demand (COD), 82% elimination was obtained at treatment costs ranging from $0.95 to USD 4.93/m^3, which formed electrical power, chemical, and electrode use. The application might be expanded to include the maritime sector. employed bipolar electrode configurations to remove 80% turbidity, 56% Chemical Oxygen Demand (COD), 90% oil and grease, and 89% Biochemical Oxygen Demand (BOD) from this sector using electrocoagulation-flocculation [22,108].

Advantages and disadvantages of electro-coagulation

Although the advantages of electrocoagulation and its achievement to resolve many environmental issues surpass its disadvantages, the two decades of research explains both. The disadvantages include high electricity consumption, especially in countries with high prices of electricity. The formation of oxide film leading to a decrease in removal efficiency [23] EC unable to treat wastewater with high electrolyte content due to the risk of a short circuit. Because of rust, the electrodes need to be changed on a regular basis. The development of layers on the electrodes that lower the electrocoagulation process's efficiency [24,109]. There is no need for chemical coagulants or microbes in EC because the sacrificial anode itself releases ions that act as coagulants. When employed as a pretreatment procedure, EC can dramatically lower energy usage while raising water quality [110]. The treated water or effluent of the EC has its own advantages as it is used in agriculture, especially for irrigation purposes [111]. Low volumes of sludge are created in EC as opposed to chemical coagulation; this sludge can be used as building materials, fertilizers, pigments and absorbents [112,113]. The production of denser and hydrophilic sludge helps decantation and makes flotation easier. EC finds application in different pollutants removal such as heavy metals, dyes and microorganisms [34,114,115].

Discussion and Future Perspective

Different electrode materials resulted in varying percentages of COD, turbidity, and ammonia removal. According to the review, aluminium electrode outperforms iron electrode in terms of 90% removal of COD and suspended solids for different wastewater treatment. Furthermore, for leachate treatment, aluminium electrode outperforms iron electrode in terms of 85% removal effectiveness for colour, turbidity, and COD. One of the most crucial factors influencing EC performance is current density. Because of the creation of bubbles and flocs, high current density resulted in greater COD removal. Different electrode materials resulted in varying percentages of COD, turbidity, and ammonia removal. According to the review, aluminium electrode outperforms iron electrode in terms of 90% removal of COD and suspended solids for different wastewater treatment. Furthermore, for leachate treatment, aluminium electrode outperforms iron electrode in terms of 85% removal effectiveness for colour, turbidity, and COD. One of the most crucial factors influencing EC performance is current density. Because of the creation of bubbles and floc, high current density resulted in greater COD removal. Aside from that, pH is regarded as a crucial aspect in EC performance [40,115]. The cathode's actions also have an impact on the pH value. Higher EC efficiency may be gained if the treatment procedure takes current density, electrode type, and pH into account. The cathode's actions also have an impact on the pH value [7,54]. Higher EC efficiency may be gained if the treatment procedure takes current density, electrode type, and pH into account. Additionally, it might be used in combination with other treatment methods to improve performance [10]. This connected system may be used to disinfect drinking water. Other recent research areas not addressed here are the use of porous electrodes, Nano electrodes, and three-dimensional electrodes. All things considered the EC process is thought to be a treatment technique that could get around a few obstacles in the process of removing heavy metals from industrial wastewater.

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